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NIGHT VISION GOGGLE ASSESSMENT TECHNIQUES WITH INCOMPATIBLE COCKPIT LIGHTING AND A MODIFIED CLASS B GOGGLE

by

Randall William Gibb

A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Masters of Science in Engineering

ARIZONA STATE UNIVERSITY

December 1996

NIGHT VISION GOGGLE ASSESSMENT TECHNIQUES

WITH INCOMPATIBLE COCKPIT LIGHTING

AND A MODIFIED CLASS B GOGGLE

by

Randall William Gibb

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ABSTRACT

Visual acuity (VA) is the standard form of measuring visual performance among pilots in the U. S. Air Force. Yet, during cockpit light evaluations using night vision goggles (NVGs), it has been noted that VA remains constant despite noticeable loss in apparent visual contrast. Therefore, contrast sensitivity (CS) may be a useful measure of visual performance under degraded viewing conditions. The objective of this research was to demonstrate that CS is a viable, additional visual performance tool in NVG cockpit light compatibility evaluations. This study investigated both NVG-aided CS and VA performance with incompatible cockpit lighting. Green and red lights, used in NVG compatible cockpits, were used to accomplish the degradation from a baseline or no-light condition. The lights were placed directly in the NVG field of view (FOV). Twenty subjects were assessed under three light conditions. The subjects viewed three newly developed NVG CS charts and two VA charts. The 3 CS charts had spatial frequencies of 3, 6, and 12 cycles per degree (cpd) and 16 levels of decreasing contrast. The two VA charts were the NVG Resolution chart and the USAF 1951 Tri-bar chart. The type of NVG used contained a new NVG Class B filter, which enables a pilot to view the heads-up display (HUD). The CS charts proved to be an effective tool in evaluating an incompatible cockpit light. The two different VA charts were compared and found to produce the same VA scores in all conditions. The combined assessment procedures of CS and VA provided an accurate visual performance assessment of an NVG under an incompatible light. The modified Class B filter demonstrated that it meets all the cockpit lighting requirements of the military specifications.

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Mr. John Martin, HTI, contributed with his knowledge of electronics and engineering abilities in the construction of the light source. He built the metal housing unit and also acted as a consultant on a variety of technical issues.

Ms. Margie McConnon, HTI, Research Communications Center, made the NVG CS charts and the experimental set-up drawing, Figure 7. Her assistance and abilities produced sturdy, professional assessment charts.

Dr. William Uttal, Arizona State University, served as the committee chairman and primary research consultant. Dr. Uttal provided outstanding feedback and ensured the research was carried out in a realistic format; the final experimental design resulted from his inputs. Also, his advice on the realities of using human subjects was very insightful.

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INTRODUCTION

Aviation accidents continue to occur despite improvements in the technology of the pilot's complex weapon systems. Though the capabilities of the machinery are improving at a rapid rate, human factors continue to cause most accidents. Flying with night vision goggles (NVGs), also known as Night Vision Imaging Systems (NVIS), is one of the most highly demanding missions a pilot can perform. NVGs have allowed aviation to enter what used to be an unapproachable environment - the darkness of night. With that capability, however, comes additional challenges to the human operator. Flying is an incredibly challenging task even under normal conditions; adding night conditions to the mix increases the "pot of potential human error." The problems associated with NVGs are well documented (Kaiser & Foyle, 1991; Berkley, 1992; Crowley, Rash, & Stevens, 1992). Some of the more serious problems flying with NVGs are: loss of resolution resulting in reduced visual acuity (VA); presence of noise (scintillation) in the goggle image resulting in a loss of contrast sensitivity (CS); reduced field of view (FOV) resulting in less peripheral information and degrading situational awareness for the pilot; limited resolution and contrast resulting in reduced depth cues; and increased scan rates due to limited FOV resulting in added stress and fatigue. These visual limitations can cause misperceptions and illusions which handicap the pilot's ability to perform the mission safely.

One of the problems facing the pilot is that for their optimum use cockpit instrument lighting must be compatible with NVGs. Most aircraft in the Air Force inventory were designed with conventional white or red lighting displays, but these are

incompatible with NVGs. An incompatible light, either externally or internally, produces a glare on the NVG visual scene, degrading image contrast and reducing the ability of the user to accurately perceive the environment. Berkley (1992) states, "overall, incompatible cockpit lighting is potentially the single most serious factor in NVG operational capability and flight safety!" (p. 4). Systems must be produced that do not degrade the performance of the NVG. To achieve compatibility with NVGs the manufacturers of cockpit lighting must meet certain military specifications. MIL-L-85762A Lighting, Aircraft, Interior, NVIS Compatible (1986) defines the requirements for NVG compatible cockpit lighting. As part of the determination of NVG compatibility, MIL-L-85762A requires that NVG-aided VA be measured with the USAF 1951 Tri-bar chart. A light is compatible if it does not degrade NVG-aided VA. The requirements are defined according to two different classes of NVGs, Class A and Class B. Recently a third class has been developed, the "modified Class B." It is unknown whether the requirements defined in MIL-L-85762A are applicable to the modified Class B NVG. Currently, the military specifications are being revised and the modified Class B filter needs to be included in the revision. Little research has been accomplished in this field since the inception of MIL-L-85762A and most of the work consists of test and evaluation of modified cockpit lighting.

Numerous attempts have been made to assess whether CS measures predict flying performance and aircraft detection and to relate CS and VA assessment techniques. Each study, however, uses a slightly different VA and CS measurement technique to assess visual performance. As will be described in detail, the results are inconclusive. VA

remains the primary measure of visual performance. Both NVG-aided VA and NVG-aided CS have been measured (Bryner, 1986; Wiley, 1989; Rabin, 1993; Bradley & Kaiser, 1994, Rabin, 1994; Rabin & McLean, 1996); but far fewer CS studies have been conducted. NVG-aided VA is normally used to assess NVG compatible cockpit lights, but CS may also be a viable measure to determine degradation. It has been noted in cockpit lighting evaluations that VA has remained unchanged despite a noticeable loss in apparent contrast. This subjective finding has stimulated interest in investigating NVG-aided CS performance under a degraded visual scene. VA and CS measure very different aspects of the visual system, and if assessed together, may provide a more complete picture of NVG visual performance.

To quantify the visual performance measures from baseline (no degraded light condition), some form of degradation needed to be introduced to the NVG visual scene. Two colored lighting filters were used to degrade the visual scene, NVIS Green and NVIS Red. NVIS Green light is used for the primary and secondary instruments and NVIS Red is used for warning indicators in NVG compatible cockpits. Both colored filters are designed to be compatible, but even too much of a compatible light may degrade the NVG. The NVIS Green was of concern due to its spectral overlap of the modified Class B filter and was the light condition of slight degradation. The NVIS Red light was used because it produced a condition of severe degradation.

The primary objective of this research was to demonstrate that CS is a useful additional visual performance measure of the effects of incompatible cockpit lighting. This study provides quantitative contrast degradation under incompatible cockpit light. A

comparison was then made between the percentage of degradation between the CS charts and the VA charts. This included examining the subject's performance within the CS charts and the two types of VA assessments, as well as comparing total degradation between all of the measures due to incompatible light. Other secondary objectives of this research were comparing the NVG Resolution chart to the USAF 1951 Tri-bar chart and determining if the modified Class B filter meets the military specifications under an NVIS Green light condition.

BACKGROUND AND LITERATURE REVIEW

The background and literature review consists of three major sections. The first section will entail the basic concepts of how an NVG works, the different classes of NVG filters, and the types of cockpit lighting that are used with NVGs. The second section will introduce the concepts of CS and VA. Finally, the literature review section will discuss unaided CS and VA research followed by NVG research on CS and VA.

The Night Vision Goggle

Reising, Antonio, and Fields (1996) state, "NVGs greatly enhance the ability to conduct night operations and are used extensively in both rotary-wing and fixed-wing operations" (p. 17). NVGs provide an intensified image of scenes illuminated by ambient light in the red and near infrared part of the electromagnetic spectrum, approximately 600 - 900 nanometers (nm). Light enters the goggle and the photons of light are converted into electrical energy by a photocathode (see Figure 1).

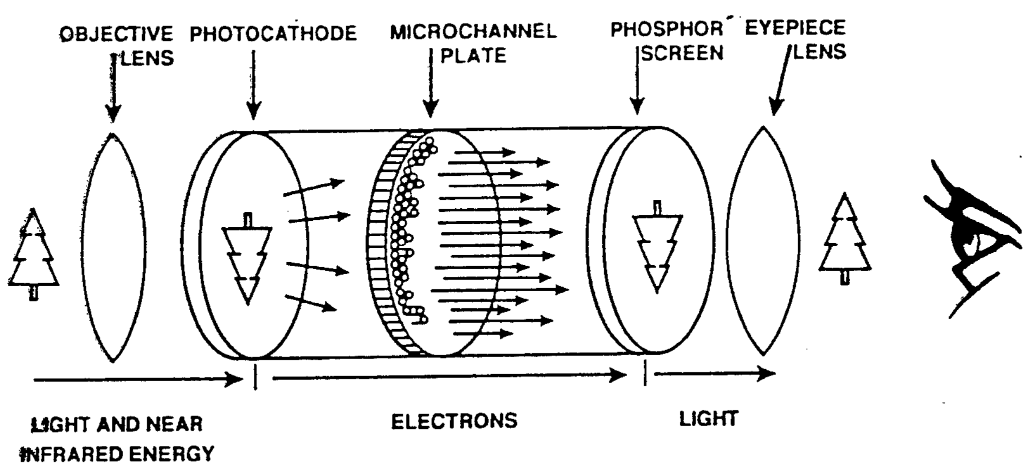

Figure 1. A model of how an NVG works.

The electrons then strike a microchannel plate, which has bent tubules, causing the electrons to impact these bent tubule walls, separating and accelerating the electrons. The electrons then strike a phosphor screen, causing the screen to illuminate and produce an image.

An increase in both the total number of electrons and their acceleration results in the intensified imagery of the NVG (on average 3000 times brighter than the original scene). Image quality is improved with compact goggle parts because of reduced dispersion of the photons and electrons.

NVGs employ an automatic brilliance control (ABC) feature which acts to maintain a constant image brightness by decreasing the intensifier gain in response to input light levels exceeding a defined threshold. An intense light source, emitting energy in that portion of the electromagnetic spectrum in which the goggle is sensitive to, can produce a veiling glare and obscure the entire image. To prevent this glare and to protect the image intensifier assembly from permanent phosphor burns, goggles use this ABC feature. The decrease in intensification is termed, "gaining down." With the decrease in gain there is a corresponding decrease in image contrast, and a loss in NVG-aided VA. If an interior light is in the spectrum that the goggle can sense then it may be incompatible and it might severely degrade NVG-aided VA and CS, especially if it is in the NVG's FOV. Incompatible light sources can be outside the NVG FOV and still degrade VA. This can happen if enough light is captured and internally reflected by the glass elements of the NVG objective lens structure to cause veiling glare. If the veiling glare is severe, it will activate the ABC and decrease the image contrast. Even if the veiling glare is not

severe, some contrast loss still may occur. This veiling glare generally is caused by an incompatible light reflected by cockpit instruments, canopy, or windscreen. Too little light creates a scintillation effect on the image. The goggle is working hard to produce a scene out of a minimum amount of light and the resulting image is like "shiny rain." This also makes the visual scene very difficult to see, in terms of contrast and acuity.

NVG Classes. MIL-L-85762A defines the requirements to achieve NVG compatibility of cockpit light. There are different requirements depending upon the Class of NVG used. The Class A goggles are filtered so they will not sense and intensify light having wavelengths shorter than the orange region of the spectrum. Class B goggles are filtered so they will not sense and intensify light having wavelengths shorter than the middle red region of the spectrum. The Class A goggle has a 625 nm minus blue objective lens filter which blocks light below that wavelength from entering the goggle. The Class B goggle has a minus blue filter at 665 nm, which allows some orange-red light to be used in the cockpit (see Figure 2).

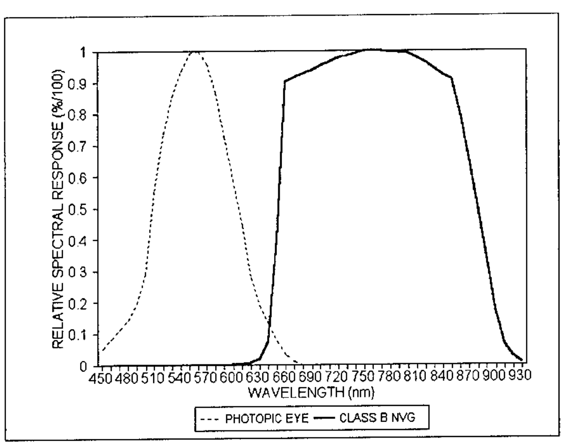

Figure 2. The graph of the spectrum of a Class B NVG and the visible spectrum. Notice the overlap of the two regions between 600 - 700 nm.

Both the Class A and Class B NVGs are defined in terms of a relative spectral response of 50%, which is at 625 or 665 nm, respectively.

A Heads-up display (HUD) has a spectral output that is mainly green, but it has some yellow in it that can be sensed by the 625 nm Class A filter. However, Class B NVGs (665 nm cutoff) do not allow for HUD readability because they do not sense the yellow. The modified Class B goggle has a "leaky green" feature added to it. This allows the particular spectrum of light that the HUD uses to be sensed by the NVG. The modified Class B NVG responds to 1% of energy at 545 nm (see Figure 3).

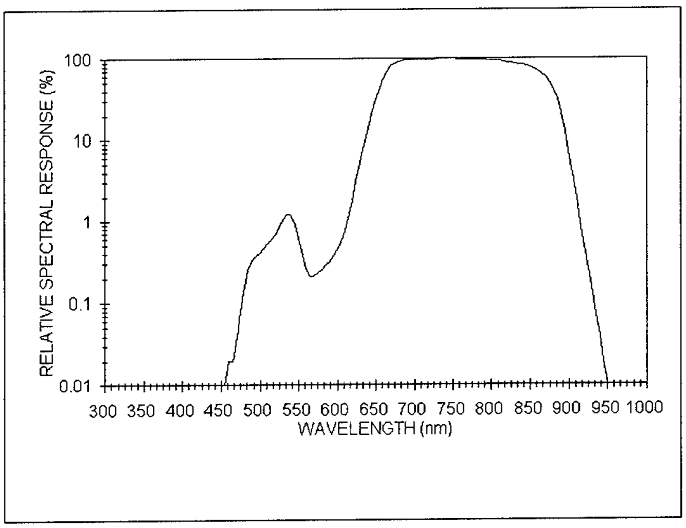

Figure 3. Spectral response of the modified Class B NVG. Notice the 1% spike at 545 nm to allow readability of the HUD as well as the 50% response at 665 nm.

When a modified Class B NVG is used, a perfectly compatible cockpit has light displays emitting energy less then 665 nm. The pilot can adjust the cockpit displays as high as necessary to read them in the dark cockpit and not degrade the image quality of the NVG. Also, the HUD is visible through the goggle due to its leaky green filter. There is concern that a normally compatible, green cockpit light can gain down the

goggle due to the leaky green feature. This is based on the spectral region of the NVIS Green A and B lights having peak intensity near 545 nm.

Cockpit Lighting. When operating NVGs, the pilot scans the outside visual scene with the goggles. To cross-check the interior instruments, the pilot must look around or under the eye piece of the NVG. The interior lights should be at a luminance that allows the pilot to easily discern the alpha-numerics of the instruments. The photopic adapted eye is sensitive to energy from 390 - 730 nm (see Figure 2). The eye is most sensitive to light at 555 nm (green light). Compatible cockpits have blue-green and green light, which is outside the spectrum of NVG sensitivity, but is near the peak sensitivity of the human eye.

Unfortunately, the majority of cockpits in the Air Force do not have NVG compatible lights. However, the Air Force is currently in the process of modifying the cockpit lighting. If the lighting is not compatible, pilots must tape over the instruments to keep them from interfering with the goggle. Another technique is to turn off all interior lighting and hang "chem-lights" around the cockpit to illuminate the needed displays. Chem-lights are disposable light sticks that are compatible with the NVG. These techniques are not adequate or safe. A study by Crowley, Rash, and Stephens (1992) surveyed 221 pilots to assess the visual illusions they experienced while wearing NVGs. Often the noted problems were misjudgments of drift, clearance, height above terrain, and altitude. Contributing factors to the illusions were inexperience and divided attention, as well as incompatible internal lighting. Pilots noted that cockpit light caused problems by reflecting off of the canopy creating disorientation and hampering readability.

To achieve compatibility and avoid losses in NVG-aided VA due to ABC, cockpit lighting should have a spectral distribution containing little or no overlap with the spectral response of the NVG. Military Specification MIL-L-85726A, defines criteria for the assessment of cockpit lighting compatibility. Due to the different filters of the two classes of NVGs, there are different criteria for defining compatibility. Reising, Antonio, and Fields (1996) explain the NVG compatibility of cockpit lights. MIL-L-85762A identifies four color coordinate ranges for cockpit lighting to be used with Class B NVGs: NVIS Green A, NVIS Green B, NVIS Yellow, and NVIS Red. NVIS Green A is used for primary crewstation lighting. A problem with NVIS Green A is that it is often unreadable under direct sunlight and it is not suitable as a color for enunciators or displays when daylight readability or attensity is crucial. NVIS Green B was established to overcome this shortcoming. It occupies a color coordinate region which is more saturated and provides better daylight readability and attensity. Both NVIS Green A and Green B spectra are outside the response range of a Class B NVG and therefore, when set at the proper brightness will not negatively impact NVG performance. However, too bright a light, even a compatible one, may degrade the NVG visual scene.

NVIS Red (a reddish orange color) is also used with Class B goggles. However, its spectral band slightly overlaps the response range of Class B NVGs, and the radiance of NVIS Red displays must be controlled to limit any negative effect on the Class B performance. NVIS Red was established to permit the use of red for caution/warning indicators and color moving map displays in Class B compatible cockpits. Although, not quantified in MIL-L-85762A, the use of NVIS Red in Class B cockpits should be limited

as much as possible because the cumulative effect of multiple NVIS Red enunciators and displays can degrade NVG performance. The amount of NVIS Red can be limited by using NVIS Green B and NVIS Yellow for caution/warning indicators. NVIS Red can severely impact Class A NVG performance, and MIL-L-85762A does not allow its use with Class A NVGs. A study by Bryner (1986) found that NVIS Red lights cause an 8% resolution degradation with the 665 nm minus blue filter of a Class B goggle when presented in the NVG FOV. When in the FOV of a 625 nm Class A goggle, the resulting degradation was 14%. It was decided that 8% degradation was acceptable for the Class B NVG since NVIS Red is primarily used as a warning indicator that only illuminates during an emergency situation. However, 14% was deemed unacceptable for the Class A goggle. The use of red colored light is the result of pilot preference because red is associated with danger. In this case it is in conflict with the spectral sensitivity of the goggle, but in small amounts considered acceptable by the Joint Logistics Commanders, who are responsible for MIL-L-85762A. Bryner's study is important and will be examined in more detail later.

Reetz (1987) explained how the standardization of military specifications in cockpit display lighting compatibility were developed with the term, NVIS Radiance (NR). This is an important publication because it states the reasoning behind the military specifications in MIL-L-85762A. Reetz (1987) defined the concept of NR in this way:

> NR quantifies the interaction of lighting components and the NVIS. Units of NR were modeled after the definition of photopic luminance, and represent the amount of energy emitted by a light source that is visible through the NVIS.

> NVIS Radiance is defined as the integral of the curve generated by multiplying the spectral radiance of a light source by the relative spectral response of the NVIS. (p. 15)

Reetz also examined the method for determining the level of NR to be acceptable. When MIL-L-85762A was written, it was agreed that, "...compatibility could be achieved if the image of the cockpit lighting, when viewed through the NVIS, were no brighter than the outside scene" (Reetz, 1987, p. 16). Reetz (1987) continues to state that in an operational setting, "...a defoliated tree is the terrain feature that is the most difficult and important to see" (p. 17). The NR of a defoliated tree illuminated by starlight was calculated by multiplying the spectral radiance of starlight by the spectral reflectivity of tree bark. This mathematical procedure produces a value of 1.7×10^{-10} NR for a Class A goggle and 1.6×10^{-10} NR for a Class B goggle. These values should not be exceeded, thus keeping "...the cockpit lights dimmer than the outside scene when viewed through the NVIS" (Reetz, 1987, p. 17). Slusher (1985) showed that the level of luminance of interior lights adjusted by pilots wearing NVGs is approximately 0.1 footlambert (fL). Consequently, the above stated NR values are the max NVIS Radiance allowed when lighting displays are illuminated to produce 0.1 fL. NVIS Green A and B are limited to the 0.1 fL criteria. There are exceptions to this figure and one is the caution/warning indicator lights. It is very important that these lights be detected immediately by the pilot. Therefore, the max NR was increased and 15 fL was assigned as the luminance criteria. The NR value for NVIS Red caution/warning lights was determined from the research of Bryner (1986).

Contrast Sensitivity and Visual Acuity

Contrast Sensitivity. Goldstein (1996) describes the spatial frequency approach to visual perception as being based on the stimulus' property of spatial frequency. The more fine-grained or detailed an object, the higher the spatial frequency. The physiological basis for this theory is that certain neurons fire to specific spatial frequencies. Properties of a visual scene's spatial frequency are waveform, contrast, spatial frequency, and orientation. A square wave grating indicates that the intensity of the grating bars alternate abruptly. A sine-wave grating represents a gradual change in intensity. The sine-wave is considered to be the most fundamental unit at the base of the spatial frequency perception theory; a square-wave is a product of numerous sine-waves. A grating's contrast is equal to its amplitude. To measure spatial frequency one black bar and one white bar is equal to one cycle in terms of specified distance of the image on the retina. This specified distance is the visual angle. If that one cycle is measured at a visual angle of 1 degree, then it has a spatial frequency of 1 cpd.

Contrast sensitivity is a measure that assesses contrast threshold at different spatial frequencies. The contrast threshold is the minimum luminance contrast between the lightest and darkest parts of a spatial pattern that will allow a subject to detect them (Boff & Lincoln, 1988). Contrast sensitivity is the reciprocal of the contrast threshold. "By measuring the contrast required for resolving the bars of a sine-wave grating at each of several spatial frequencies, an observer's contrast sensitivity function is obtained and this information reveals far more about visual ability than a one-number resolution value" (Boff & Lincoln, 1988, p. 200).

Goldstein (1996) describes the contrast sensitivity function (CSF) as a plot of the contrast needed to see a particular grating versus the grating's spatial frequency. The CSF is formed by measuring individual spatial frequencies and decreasing the amount of contrast until the subject can no longer discriminate the orientation of the grating. The normal peak of contrast sensitivity is near 2 - 4 cpd. Sensitivity values drop off prior and after this point. In other words, lower frequencies and higher frequencies need much more contrast for the visual system to detect them, where as the spatial frequencies in the 2 - 4 cpd range can be seen with very little contrast.

Through the years, numerous different measurement techniques have been developed to quantify an individual's CS as quickly and easily as VA is measured. One method developed by Arthur Ginsburg in 1984, consisted of five levels of increasing spatial frequencies and nine levels of contrast (Shaply & Lam, 1993). The subject would simply report the lowest level of contrast readable at each sine-wave spatial frequency and those points then were plotted and formed the CSF. The Ginsburg chart would later be published as the "Vistech chart", which has been used in CS research (Corwin & Richman, 1986; O'Neal & Miller, 1988). Shaply and Lam (1993) report that recently, many CS studies have not used sine-wave gratings. They state, "however theoretically appealing the idea of measuring contrast sensitivity using sine-wave gratings may be, there is little or no evidence to show that measurements made with this particular test pattern are of any especially great clinical relevance and that practical considerations are of overriding significance" (Shaply & Lam, 1993, p. 264). Shaply and Lam (1993) continue in their generalization of CS measurement techniques, "...an accurate measure of

contrast threshold is not simply a matter of testing using enough different stimuli with sufficiently closely spaced levels of contrast, it is more a matter of making a large enough number of judgments to allow for statistical reliability; it is a matter of spending enough time making the measurements" (p. 265).

According to Hawkins (1987), "conventional eye tests are generally adequate for predicting visual performance under normal conditions...yet, two individuals who have been rated as having 20/20 vision may differ greatly in their visual performance when it comes to tasks such as seeing signposts or pedestrians when driving at night" (p. 106). If driving at night is not "normal", then certainly flying with NVGs would also be classified as not normal. This quote by Hawkins hints at the possible inadequacies of only assessing VA in visual performance tests. The following section will introduce some of the basic concepts of VA.

Visual Acuity. To accurately determine if a light is incompatible, MIL-L-85762A specifies that NVG-aided VA be assessed to quantify the degraded visual scene. A compatible light should not degrade NVG-aided VA. Boff and Lincoln (1988) define visual acuity as "the ability to discriminate fine objects or the details of objects subtending small angles at the observer's eye" (p. 199). Boff and Lincoln (1988) continue by stating, "most VA tests measure the size of the smallest pattern of detail that can be distinguished, in minutes of arc of visual angle subtended at the eye" (p. 199). Usually VA is expressed in terms of visual angle to allow comparison between different visual performance measures. Normal VA is considered to be 1.0 (a resolution of 1 minute of arc) and is equivalent to a Snellen acuity of 20/20 vision (Boff & Lincoln,

1988). Numerous different types of tests can be used to measure VA. Boff and Lincoln (1988) point out that big differences between observers and studies in VA values occur because of "differences in the confidence of judgments, criteria of visibility or separation, scoring methods, instructions, training, and viewing conditions" (p. 199). Also, some measures are highly subjective and require the subject to simply report which column and row is distinguishable, without identifying a target's configuration. Most other measures, Snellen letters, Landolt ring, E-chart, and square-wave gratings, force the subject to specify the particulars of a specific VA. Another problem between different measures is that the subjects may memorize letters and/or make guesses.

Boff and Lincoln (1988) stress that, "correlation between different visual acuity test scores is low...the nature of the visual task to be performed, therefore should determine the type of test and target to measure" (p. 200). The standard VA letter charts examine minimum separability and the result is a restricted measurement of a high-contrast target. VA assessments do not address the ability to see shapes or forms of various contrast. Shape discrimination is best judged by low spatial frequency testing, which measures the information content during low-illumination and long viewing distances. Boff and Lincoln are stating more specifically what Hawkins had hinted at in the CS discussion. VA does not assess the entire visual performance abilities of an individual. There is concern whether a pilot with standard 20/20 vision possess the visual abilities that complex visual environments, such as night flying and NVGs demand. The results of identifying whether CS or VA are better at predicting performance are inconclusive. The following section investigates unaided CS and VA research.

Literature Review

Unaided CS and VA Research. CS and VA measures have long been used to predict performance of aviators. Kruk, Regan, Beverley, and Longridge (1981) explored the correlations between the visual measures and flying performance. They compared 13 different visual assessments with flying performance in a simulator during low-visibility landing conditions. Though it was not a major finding, they were surprised that contrast threshold correlated weakly with landing performance and flying grades. Their results demonstrated the lack of correlation of CS. They argued that two pilots having equal Snellen VA may not have similar CS. By only testing Snellen VA, occasionally a pilot's poor contrast threshold in low-visibility conditions would not be discovered using current visual assessment procedures. Kruk, Regan, Beverley, and Longridge (1983) conducted another study assessing the relationship between flying performance and visual measurements. Again, they found no correlation between grating contrast threshold and flying maneuvers. They explained their results stating that, "...intersubject differences were sufficiently small in contrast threshold and did not appreciably contribute to intersubject differences in landing performance" (Kruk et al., 1983, p. 463). Another study by Kruk and Regan (1983), found similar results. Not only did contrast threshold fail to correlate with flying performance, but Snellen acuity also did not correlate with visual acquisition distance during flying maneuvers. This was explained by the narrow range of VA scores of the subjects. A major limitation to the research accomplished in all three Kruk and Regan studies is that their measure of CS was only investigated at one

spatial frequency, 5 cpd. In the following studies conducted by Ginsburg, CS was measured over a much broader span of frequencies, 1 - 24 cpd.

Ginsburg, Evans, Sekule, and Harp (1982), investigated whether a pilot's CS could predict their performance flying an aircraft simulator. Eleven pilots had their VA measured using standard Snellen letters at ten feet. These tests were administered in photopic and scotopic viewing conditions. CS was measured using a computer monitor and sinusoidal gratings at frequencies of 1, 2, 4, 8, 16, and 24 cpd at different levels of contrast. The flying task involved detecting the presence of an aircraft on the runway while approaching to land. The strongest correlations were between the peak region of scotopic contrast sensitivity and slant range detection rate. VA did not correlate with aircraft detection. Also, correlations between VA and CS were very low. Ginsburg et al. (1982) stated, "CS may have predictive value for other complex visual tasks in aviation and motor vehicle operation" (p. 107). Ginsburg et al. (1982) concluded their research by stating, "...our results raise new doubts about the relation between standard clinical tests of vision [visual acuity tests] and patients' performance in complex visual environments" (p. 107).

In another study, Ginsburg, Easterly, and Evans (1983) found that CS, not VA, can predict target detection of aircraft. They found that the standard VA tests of black and white letters do not relate to the real world and are inadequate to measure visual sensitivities over the required range of sizes and contrasts needed. Eighty-four pilots had their VA measured with the standard Snellen letter chart. Their CS was measured by a computer that displayed sine-wave gratings at controlled levels of frequency and contrast.

The frequencies used were 1, 2, 4, 8, 16, and 24 cpd. Each subject was tested on his/her ability to identify when an approaching airplane was "in sight." The most significant correlations were made at 8, 16, and 24 cpd, the steepest portion of the CSF. VA correlated with detection range on only 3 of 10 trials. Ginsburg et al. (1983) concluded their study by stating, "pilots having increased contrast sensitivity were able to detect an approaching aircraft at significantly greater distances and more quickly than a less sensitive pilot" (p. 272).

O'Neal and Miller (1988) examined this growing debate over whether VA or CS is a better predictor of flight performance. They assessed the CSF of 67 pilots using a Vistech VCTS 6500 chart and computer generated spatial frequencies at differing contrasts. VA was tested at three different levels of contrast using a Regan chart. The field portion of the study consisted of the pilots visually detecting an approaching Northrop T-38 Talon. Their results showed no significant correlation between VA and CS with aircraft detection. They found peak sensitivity at 3 cpd. Neither VA or CS scores could predict the best performance on the visual detection task. VA was better at predicting worst detection performance than CS scores. O'Neal and Miller (1988) point out that the difference between their study and Ginsburg's et al. (1983) research may be due to "...differences in measuring and quantifying visual acuity and in measuring contrast sensitivity" (p. 22). They also advocate that much more comprehensive research needs to be done in this area.

Rabin (1995) looked at a VA test versus small letter contrast sensitivity (SLCS). Previously Rabin had found that small letter contrast sensitivity was more sensitive than

VA to factors such as, defocus and stimulus intensity. His major objective of the study was to investigate time-limited visual resolution to predict operational performance. Subjects observed Snellen letters on a computer monitor and identified the letter to assess their VA and SLCS. His findings demonstrate the greater sensitivity of the SLCS than VA to factors that affect visual resolution. The steepest point of the CSF occurs near the acuity limit, (30 cycles per degree equals 20/20 Snellen). Therefore, any degradation of the visual scene, like defocus that affects VA, greatly affected SLCS in a negative fashion. Rabin (1995) states that, "...SLCS also provides a more discriminating approach for identifying candidates for occupations requiring unique visual abilities, such as those in space and aviation" (p. 282).

Night Vision Goggle Research. The previous discussion has focused entirely on unaided visual performance. However, similar visual performance measures have been used to assess performance with NVGs. Wiley (1989) studied 10 subject's NVG-aided VA with a computer. He varied illumination level and contrast and used the Snellen letter "E" as the measurement target. Wiley's major focus was on stereopsis, which he found is greatly reduced using NVGs. VA tests did not reveal anything significant except that the unaided eye performed much worse under the quarter moon and low contrast conditions compared to the NVG user. VA went from 20/400, unaided, in quarter moon and 35% contrast, to 20/90 with NVGs. NVGs improved from those conditions to 20/70 with quarter moon and 94% contrast. It should be emphasized that with the same illumination conditions, the 59% contrast increase improved VA from 20/90 to 20/70, a

28% improvement. It was determined that real world scenes would have 25 - 50% contrast levels and that anything above that is not operationally relevant.

DeVilbiss and Antonio (1994) were concerned with the awareness of the NVG user. The motivation for their study was to quantify the goggle pre-flight procedures to allow the user to know exactly the visual performance allowed (limited) when using the NVG. Proper pre-flight adjustment procedures are required because reduced VA can frequently go undetected. "Without controlled conditions...it is not physiologically possible for an individual to quantify visual acuity" (DeVilbiss & Antonio, 1994, p. 846). This undetected loss in acuity can make the pilot prone to all of the previously mentioned visual illusions and misperceptions that plague NVG users. DeVilbiss and Antonio introduced the NVG Resolution Chart developed by Armstrong Laboratory's Visual Displays Branch of the Crew Systems Directorate. The chart provides nine visual targets (20/35, 20/40, 20/45, 20/50, 20/60, 20/70, 20/80, 20/90, 20/100 visual acuity) which are used to objectively document goggle performance. If eight of the nine grating patterns can be seen then a VA of 20/40 is obtained. The major finding of this study was that there was no significant difference between using the 3 x 3 NVG Resolution chart versus individual acuity grating patterns; thus, validating the use of the chart. This chart has recently been modified by Armstrong Laboratory, Aircrew Research Division, to reflect the better resolution provided by newer NVGs.

In a very similar study, DeVilbiss, Antonio, and Fiedler (1994) tested 218 USAF aircrew members for their NVG adjustment procedures. They tested each individual in an eye lane using their usual NVG pre-flight adjustment procedure, then presented the

NVG Resolution chart and further adjusted their goggles, and finally, after participating in NVG adjustment instruction course, adjusted their goggles again. Each time the subject's VA measure was recorded. At each level of added instruction, the goggle adjustment procedure resulted in a significantly improved VA. Initially the average NVG-aided VA score was 20/50 - 20/55, after using the NVG Resolution chart the average VA improved to 20/45, and then after the instructional class the final VA improved to 20/35 - 20/40. This validated the use of the NVG Resolution chart and the NVG instruction course at Armstrong Laboratory.

Rabin (1994) researched vernier acuity levels with NVGs . Vernier acuity is the ability to differentiate lateral displacement. This had operational relevance to the aiming of a sight onto a target. Five subjects used different levels of illumination between quarter moon and starlight and were tested using square-wave gratings at 6 cpd. Rabin found that any conditions that reduce contrast through the NVGs will impair vernier alignment performance (the targeting tasks). He compared vernier acuity performance with and without NVG use. Vernier thresholds through the NVGs were much higher than values recorded under the same conditions without the goggles. Rabin's (1994) findings indicate that, "...a ten-fold reduction in contrast will produce a five to seven times reduction in vernier performance with the NVGs" (p. 2). This reduction in vernier acuity could not be explained by the brightness, color, or resolution of the NVG, but could be attributed to the difference in contrast sensitivity with and without the goggle.

Bradley and Kaiser (1994) evaluated VA under five different illumination conditions. Their realization of the ongoing debate of VA and CS to predict visual

performance in aviation was acknowledged by stating, "in spite of the obvious criticism that very few operational scenarios require NVG users to read fine print, measures of visual acuity are still the standard visual metric employed in NVG studies" (Bradley & Kaiser, 1994, p. 4). Their experimental design consisted of three different contrasts, 99, 40, and 10%. A computer was used to present letters varying in size and contrast to the subject. An interesting finding of this study was that, though the benefits of the NVG are predominantly in foveal vision, improved visual performance was also noted to 20 degrees eccentricity; peripheral vision is improved. The author's statements toward the limitations of VA tests with NVGs emphasizes the need to research and create an accepted NVG-aided CS measurement.

NVG-aided VA measured in the aircraft has revealed that cockpit lighting and transparencies (canopy, windscreen, HUD) can cause degradation. In a study to examine a modified F-16 cockpit for NVG compatibility, Reising and Antonio (1994) measured the NVIS Radiance of several instrument displays and used the NVG Resolution chart to measure the effects of cockpit lighting and transparencies on NVG-aided VA. This particular study also demonstrates a methodology of testing cockpit compatibility with the NVG Resolution chart instead of the USAF 1951 Tri-bar chart. The results showed that NVG-aided VA was degraded when viewed through the HUD and canopy, from 20/45 to 20/55. However, with the cockpit display lights adjusted to appropriate nighttime levels, the NVG-aided VA was not degraded and the cockpit was declared NVG-compatible.

A similar study of a C-130H3 cockpit was examined by Reising, Grable, Stearns, Craig, and Pinkus (1995). Again, NVIS Radiance was measured on all instrument displays and cockpit lights. This time two different VA tests were conducted. One test used the standard NVG Resolution chart and the other used the USAF 1951 Tri-bar chart, specified in MIL-L-85762A. The USAF 1951 Tri-bar chart is believed to create biases and limitations when viewing it. This is because the chart is organized in a standard pattern, three horizontal bars next to three vertical bars. This pattern is repeated and is always known to the observer. This does not force the observer to inform a recorder what is seen. It is a subjective measurement because the observer simply states which line he/she thinks they can see. The NVG Resolution chart can be rotated four different ways and the observer must state whether the grating is horizontal or vertical. If they are unable to state the pattern direction then they can not see that level of acuity. Using the NVG Resolution chart the incompatible cockpit light degraded NVG-aided VA from 20/55 to 20/60. One subject who had demonstrated a 10% loss in VA using the NVG Resolution chart did <u>not</u> perceive a loss in acuity using the USAF 1951 Tri-bar chart during the windscreen transmissivity assessment. Because different results were obtained with the different VA measurement techniques, concern was raised that the subjectiveness of the USAF 1951 Tri-bar chart prevents accurate NVG-aided VA assessments. It is believed that only subjects experienced with the USAF 1951 Tri-bar chart can use it to accurately assess NVG-aided VA. Under strict interpretation of MIL-L-85762A no loss in VA is allowed to occur due to cockpit lighting. The cockpit did not meet the Class A requirements (the Class B was not assessed). The results also revealed

that 60% of infrared energy is blocked by the windscreen of the C-130; a reduction of more than half the energy sensed by the NVG. One last point that this study brought out was that a C-130H3 has several NVIS Red lights and if more than one were to illuminate it could definitely degrade NVG-aided VA.

Reising, Martin, and Berkley (1996) evaluated a Class A and a modified Class B NVG filter in two different goggle types (F4949D and AN/AVS-9). They conducted two different viewing conditions of NVG-aided VA, tests with incompatible lighting and tests with a HUD. The measurements were taken in the cockpits of the following aircraft: F-15C, F-16C, C-17A, C-130, and A/OA-10. Their methodology was very similar to the previous Reising et al. (1995) study. Their findings revealed no significant differences between the F4949D and the AN/AVS-9 goggle types with the different filters. Comparing the Class A and modified Class B filters and their spectral response on the two goggles, they differed by 12.3% for the AN/AVS-9 and 13.5% for the F4949Ds. However, since the NVG-aided VA did not differ between the different goggle types, this difference in spectral response is not large enough to affect NVG-aided VA. NVG-aided VA was not degraded in any of the cockpits due to incompatible light. The mean VA of the four aircraft are as follows: F-15C = 20/50, F-16C = 20/35, C-17A = 20/55, and MC-130 = 20/40. Also tested was the HUD readability in the aircraft with the subjects wearing the modified Class B NVG. Reising et al. (1996) found that HUD readability provided optimal brightness and clarity of intensified HUD information in the aircraft. In addition, they measured the effect of green cockpit lighting on NVG-aided VA with the modified Class B filter in the MC-130H Talon II aircraft. This aircraft has numerous

green NVG compatible lights, the most of any NVG compatible aircraft (worst case scenario test). Their results found that the green light, although sensed by the NVG, did not degrade visual performance. Based upon this finding, the authors concluded that the modified Class B filter is compatible with all Air Force aircraft containing NVG compatible lighting.

Rabin (1993) prefaced his study by stating that few studies had looked at CS using NVGs. He was motivated to investigate CS using NVGs because "...acuity provides only the limit of resolution, while contrast sensitivity can provide a more comprehensive index of visual function over a range of stimulus sizes" (Rabin, 1993, p. 706). The testing chart used by Rabin was a computer generated chart of letters of constant size but decreasing contrast. It was designed to provide an index of spatial frequencies near the peak of the CSF. Contrast ranged from 64 to 2%, using the Michelson formula (C = Lmax - Lmin/Lmax + Lmin). The spatial frequencies used were 0.5, 1.0, 2.0, and 4.0 cpd. Illumination levels varied from full moon, quarter moon, starlight, and overcast. Rabin's subjects used their right eye and a monocular night vision device. His results of CS at different illumination levels matched the standard CSF; full moon had the better visual performance and overcast the worst. Another conclusion reached was that the reduction in contrast sensitivity using an NVIS in decreasing night sky illumination is greater for objects of smaller size. In other words, higher spatial frequencies show much more degradation in CS than lower spatial frequencies. Rabin's study provided initial quantitative estimates of the effects of illumination and contrast on CS while using NVGs.

In one of the most recent studies, Rabin and McLean (1996) investigated the difference between phosphor colors in NVGs. Currently P22, a deep green color, is the phosphor used in NVGs. Future goggles will use P43, a more yellowish green. They examined whether the color, each one or mixed, impacted the goggle user. They measured VA, CS, flicker sensitivity, and dynamic CS using different phosphor colors. Six subjects viewed a computer which had software generated letters presented for the VA and CS measurements. The VA letters had a contrast of 93% and the contrast for the CS tests was decreased in 0.1 log unit steps. Rabin and McLean tested at the steep, descending portion of the CSF where small changes in VA are associated with larger changes in CS. The size of the letters in the CS tests were equivalent to 20/50, 20/100, and 20/200 in all light conditions (full moon, quarter moon, starlight, and overcast). They found that the color of the resulting phosphor image did not impact any of the visual performance measurements. The methodology used in this study was interesting and continued the comparison of both VA and CS in NVG research.

One of the earliest studies investigating the relationship between different NVG classes, cockpit lighting and NVG-aided VA was carried out by Bryner (1986). She specifically studied the effects of NVIS Red cockpit lighting on NVGs. The motivation of the research concerned red warning indicators in the cockpits of aircraft that use NVGs. Red has the longest wavelength of visible light and falls under the spectrum of the NVG sensitivity range, in the overlap region between visible light and infrared. Therefore, "red lighting is generally considered unacceptable for NVIS compatibility

because the bulk of its energy lies in the spectral region in which the NVIS is sensitive" (Bryner, 1986, p. 1). Bryner investigated both Class A and Class B filters. She tested twenty subjects that were positioned 20 feet from a USAF 1951 Tri-bar chart. At arm's length from each subject was a computer screen which illuminated different instrument display lights. The subjects were to keep the indicator light in the center of their FOV and take a resolution reading. The findings of this study were mentioned earlier in this paper. A Class A 625 nm minus blue filter producing a NR of 3.3×10^{-7}, resulted in a 14% resolution degradation. A Class B 665 nm minus blue filter producing a NR of 1.4×10^{-7}, resulted in an 8% resolution degradation. It was determined that the 8% degradation was acceptable since the light only illuminates during emergency situations and would quickly attract the pilot's attention to look under the goggle to scan the warnings and instrument lights. Bryner's study is important because it is one of a very few studies to research incompatible lighting in cockpits. She also used a USAF 1951 Tri-bar chart to measure VA and illumination was at starlight levels, which is specified in MIL-L-85762A.

Summary

MIL-L-85762A specifies using a USAF 1951 Tri-bar chart to test NVG-aided VA with cockpit lighting compatibility tests at starlight conditions. This VA measurement technique has limitations and the Air Force has developed the NVG Resolution charts to possibly replace the Tri-bar chart. These charts and procedures were established by DeVilbiss and Antonio (1994) and were further refined in Reising, Antonio, and Fields

(1996). Furthermore, differences have been obtained when comparing the performance measures with both charts under identical cockpit lighting conditions (Reising et al., 1995). NVG-aided CS has never been used as a measure to assess effects of incompatible cockpit light, especially on the steepest portion of the CSF, near optimum VA (Rabin & McLean, 1996). VA and CS measure different aspects of visual performance. NVG-aided CS may prove to be a necessary, additional performance measure that should accompany NVG-aided VA tests under incompatible light conditions.

The primary objective of the present research was to examine the usefulness of CS measures with NVG incompatible light assessments. Three NVG CS charts were developed and used to assess the effects of incompatible cockpit lighting using a modified Class B NVG. The NVG CS charts had spatial frequencies of 3, 6, and 12 cpd (approximately equivalent to 20/200, 20/100, and 20/50 Snellen VA, respectively). Two different VA assessment charts were also used to assess the effects of incompatible cockpit lighting. The two VA charts were an NVG Resolution chart and a USAF 1951 Tri-bar chart. A comparison of the two VA charts was accomplished to determine if they produce the same acuity levels. Three light conditions were used to degrade the NVG scene: 1) no light condition (baseline); 2) a green light condition (slight degradation); and 3) a red light condition (more severe degradation). It was mentioned earlier that a concern with the modified Class B goggle is that the leaky green feature could leak compatible green light to the intensifier, thus degrading the visual performance and becoming an incompatible light. This concern was addressed by Reising, Martin, and Berkley (1996). They demonstrated in an MC-130H that large amounts of NVIS Green

A/B light did not degrade the visual scene with a modified Class B goggle. The leaky green feature allows 1% of 545 nm into the NVG. An intent of this study was to demonstrate that an unusually large amount of green cockpit light is needed to just slightly degrade the visual scene of the goggle. To address this concern the amount of NVIS Radiance required to effect visual performance with the modified Class B was quantified in a pilot study.

METHOD

Subjects

Twenty-two subjects (20 males and 2 females) participated in the experiment. Two of the subject's data were not considered in any of the statistical analyses. This was due to one subject that had outlier VA scores and the other admitted to and demonstrated a significant amount of guessing on the chart patterns. Therefore, a sample size of twenty subjects was used for all analyses and discussions. Six of the subjects were pilots (five fixed-wing and one helicopter pilot) and three of those six were NVG experienced. The average age of the subjects was 31.1, ranging from 22 to 51 years old. The subjects who were inexperienced with using NVGs were assisted in the handling and focusing of the goggles. All of the subjects received specific training in the use of the F4949D NVG and the proper adjustment procedures used to achieve optimum focus. All of the subjects were instructed on how to read the USAF 1951 Tri-bar chart prior to starting the experiment and an unaided VA measure was taken. The subjects' average VA was 20/18.65, which is better than the considered normal vision of 20/20 Snellen acuity. All of the subjects were volunteers and were informed prior to the start of data collection that they could withdraw from the research at any time.

Experimental Design

The experimental design consisted of two within subjects designs or repeated-measures analysis. The repeated-measures analysis eliminates individual differences because each subject participated in all test conditions. The variance between treatments is computed by only using the treatment effect and experimental error. The CS analysis

was a 3 x 3 design. It consisted of three CS spatial frequencies and three light conditions. The VA analysis was a 2 x 3 design. It consisted of the two different VA charts and three light conditions. The independent variables were: 1) visual performance measure (NVG Resolution chart, USAF 1951 Tri-bar chart, 3 NVG CS charts - 3, 6, and 12 cpd) and 2) light conditions (baseline - no light, NVIS Green B and NVIS Red). The dependent variable was the visual assessment score, either a VA or contrast value. The null hypotheses were as follows: 1) the three CS charts will show equal percentage degradation; 2) the NVG Resolution chart and the USAF 1951 Tri-bar chart will both produce equal VA scores; 3) the effect of the different light conditions will be equal. Each subject accomplished a total of 15 trials between both CS and VA assessments. The order of the charts presented and the lighting conditions were randomized. An Analysis of Variance (ANOVA) using SPSS for Windows 6.0 was conducted to assess any statistical significance between the variables at a significance level of .05.

Stimuli and Apparatus

Night Vision Goggle. A modified Class B NVG filter was used on an ITT F4949D NVG. This NVG has 50% spectral response at 665 nm and 1% spectral response at 545 nm.

NVG Resolution Chart. The NVG Resolution chart was used to assess NVG-aided VA (see Figure 4). It was positioned randomly in orientation but always placed 20 feet (6.096) from the subject. The NVG chart was the same design as described in Reising, Antonio, and Fields (1995). One of two charts was used. Each chart contained 16 horizontally and vertically oriented patterns varying in five foot increments of Snellen

acuity. Patterns of Chart 1 varied from 20/20 to 20/70, with the 20/35 to 20/55 patterns presented twice. Patterns on Chart 2 varied from 20/50 to 20/90, with the 20/60 through 20/90 patterns presented twice. Each square was 4 x 4 inches (10.1 x 10.1 cm), black and white, with 50% modulation contrast.

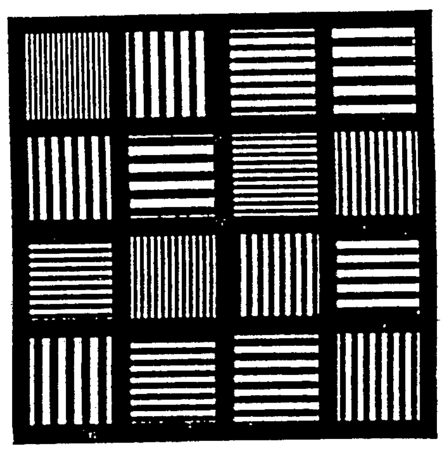

Figure 4. The NVG Resolution chart.

USAF 1951 Tri-bar Chart. The USAF 1951 Medium Contrast Resolution Resolving Power Target (Tri-bar chart) was used in measuring NVG-aided VA (see Figure 5).

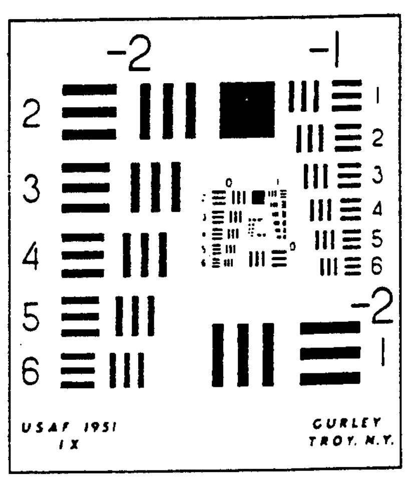

Figure 5. The USAF 1951 Tri-bar chart.

This chart was placed 20 ft (6.096 m) from the subject. It had numbered rows and columns. The subject informed the recorder which element associated with a specific row and column that was clearly resolvable. An element consisted of two target patterns of three lines each, at right angles to each other; either vertical or horizontal. The width of the line was equal to the width of the space and the line length was five times the width. The patterns of elements decreased in resolution by 11%. The modulation contrast of the chart was 70%. The size of the chart was 40 x 40 inches (101.6 cm x 101.6 cm)

NVG Contrast Sensitivity Chart. A commercially available Vistech VCTS 6500 CS chart was to be used in this study. However, pilot data revealed that the majority of spatial frequencies could not be seen with NVGs. Therefore, an NVG-aided CS chart had to be developed for this research. Two factors were considered in the design of the charts, the chosen spatial frequencies and the range of contrast. The majority of NVG-aided VA has been found to be in the range of 20/45 to 20/60 (13 - 10 cpd) for the starlight conditions. This would serve as the highest spatial frequency used. Other CS studies were investigated to replicate their use of spatial frequencies. Also, the contrast must range from, “easily discernible” to “unable to see.”

The NVG CS chart that was developed specifically for this research was used to measure the contrast sensitivity of the subjects. The charts were similar to the NVG Resolution charts. The NVG Resolution chart consisted of the same contrast and different spatial frequencies, whereas the NVG CS charts consisted of the same spatial frequency but at different contrasts. Three different spatial frequencies were used, 3, 6,

and 12 cpd at 16 levels of contrast each. Table 1 lists the different levels of contrast that the three NVG CS charts used. The cycles per degree on the NVG CS chart are approximately equivalent to 20/200, 20/100, and 20/50 Snellen acuity (3, 6, and 12 cpd, respectively). The charts were made using a software program developed at Wright-Patterson AFB, Ohio. This same software program was used to develop the NVG Resolution charts. They were printed on a laser jet printer. The contrast level was calculated by measuring luminance with a Photo Research PR-1980A Photometer and applying the Michelson contrast formula.

Table 1

Contrast Levels used on the NVG CS Charts

12 cpd Chart	6 cpd Chart	3 cpd Chart
88.8	44.0	24.8
80.7	39.0	21.6
69.1	31.8	18.1
63.7	28.0	15.3
55.2	25.0	13.8
49.5	21.0	12.3
44.4	17.9	11.6
42.3	16.2	9.9
35.3	14.3	9.1
31.5	12.0	8.0
28.2	11.6	7.3
26.1	10.8	6.6
22.9	8.5	4.7
18.3	7.6	4.1
17.4	6.7	3.9
16.8	4.1	3.0

A review of Boff and Lincoln (1988) verified that contrast variation of 0.05 log units had been used previously in CS experiments. This study used only approximate 0.05 log unit levels in decreasing contrast due to the inability of the software program and the laser printer to produce exact 0.05 log unit contrast values.

Illuminator. All visual performance charts were illuminated at starlight conditions by a Hoffman Engineering Corporation LS-65-GS Integrating sphere. The sphere provided near uniform light distribution on the charts. The illumination level was measured with a Photo Research PR-1530AR NviSpot radiometer fitted with a Class B filter. The illumination level was at starlight defined for Class B NVGs, 1.6×10^{-10} NR (specified in MIL-L-85762A). The Class B military specifications were used to demonstrate that the modified Class B filter could meet the same requirements as the regular Class B filter.

Cockpit Light Source. A small metal housing was constructed to hold a Tungsten halogen lamp, 20W/ 24V. Protruding from the metal housing was a one inch (2.54 cm) diameter metal tube that extended 2 inches (5.08 cm). The different colored filter devices were placed over this part of the light source. The metal housing was attached to a metal bar to elevate the light source 19 inches (48.3 cm) above the table. The light source and bar were secured to the table at an angle of approximately 10 degrees. This placed the light source nine and a half inches away from the NVG and aimed directly up and into the NVG objective lens. The light source was approximately 20 inches (50.8 cm) from the subject. The placement of the light was based on the position of the fire-warning lights in the cockpit of an A-10 aircraft. When a subject viewed the charts through the NVGs, the light source was located in the middle, bottom center of their FOV. It did not restrict the viewing of any part of the visual assessment charts. The light source was connected to a DC power source. The intensity of the light was controlled by a voltage regulator on the

power source. The light source's metal housing was covered with black tape to inhibit any light leaks.

Two different colored NVIS filters were attached to the small end of an aluminum, cone shaped device. The metal tube protruding from the light source was inserted into the larger end of the cone. The small end of the cone with the filter attached to it came to rest on the tube from the light source. One aluminum cone had a Wamco, Inc., NVIS Green B (NV-2GB) attached to the small end. Its spectral transmission was 400 - 590 nm, with peak transmission at 520 nm (see Figure 6). For the green light condition the voltage was set to 22V. Its Class B radiance was 4 x 10^{-7} and the measured footlamberts of the green filter was 259. The footlamberts were measured with a Minolta LS-110 Photometer. The second aluminum cone had a Wamco, Inc., NVIS Red (NV-6RC-10) attached to the small end. Its spectral transmission was 500 - 650 nm, with peak transmission at 600 nm (see Figure 6).

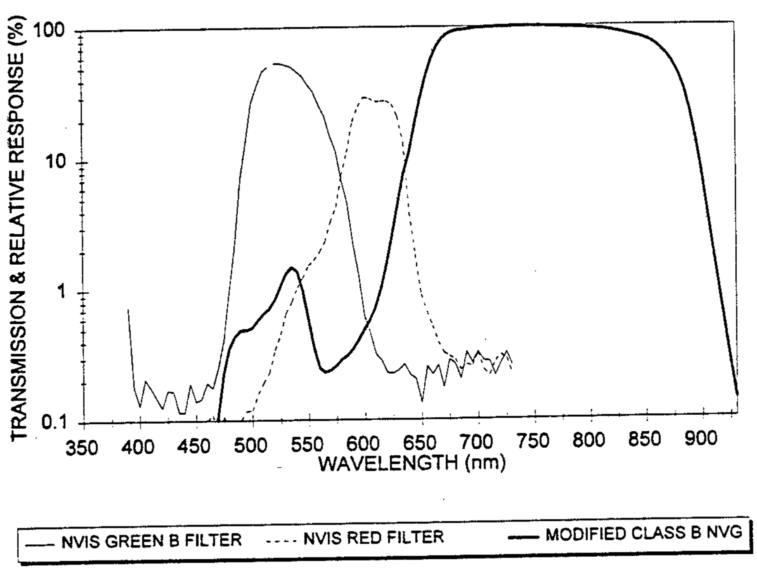

Figure 6. The NVIS Green B and NVIS Red spectral regions vs. the modified Class B NVG spectral region.

The voltage set for the red light condition was 24V. Its Class B radiance was 2.2 x 10^{-6} and the measured footlamberts of the red filter was 200. It was also measured by the same method as the green filter.

The NVIS Green B was used because it had an intense spectral distribution near the 545 nm region, thus testing the leaky green feature of the modified Class B goggle. The NVIS Red was used to create a more severe visual degradation than the green filter.

Procedure

The procedures for the experiment followed Bryner's (1986) study. All subjects were evaluated in an eye lane located at Armstrong Laboratory, Williams Gateway Airport, Mesa, Arizona. The eye lane was approximately 36 ft long and 7 ft wide. Prior to the lights being extinguished, subjects were instructed on how to read the USAF 1951 Tri-bar chart. During this explanation, each subject read the minimum resolvable pattern that was distinguishable from 20 ft. This ensured that each subject was familiar with the chart and also provided an unaided baseline VA score. The subject was then seated and the lights were turned off in the eye lane.

Approximately 10 minutes were used to obtain basic information from the subjects, read the experimental instructions to the subjects, and have the subjects sign the consent form (Appendix A). Also, the subjects were shown how to adjust the chin rest and focus the NVGs. All of this was done in the dark to allow the subjects to adapt to the conditions. An NVG Resolution chart, with nine gratings varying from 20/20 to 20/60, was used to focus the goggles. The light condition for the focusing of the goggles was approximately full moon illumination. Each subject was instructed how to read the NVG

Resolution chart and all subjects' NVG-aided VA was at least 20/35. Many of the subjects' NVG-aided VA was 20/30. The entire experimental procedure took approximately one hour. Figure 7 depicts the experimental set-up in the eye lane.

The experimental data recorder was seated approximately 22 ft from the subject, next to the visual assessment charts. This position put the recorder on the far left of the subject's FOV. As the subject read the various chart's patterns, the recorder checked to determine if it was correct and recorded the subject's response. If an incorrect response was given it was circled by the recorder on the data collection sheet. The recorder only communicated with the subject to ensure that what the subject stated for a particular row and column was correctly annotated.

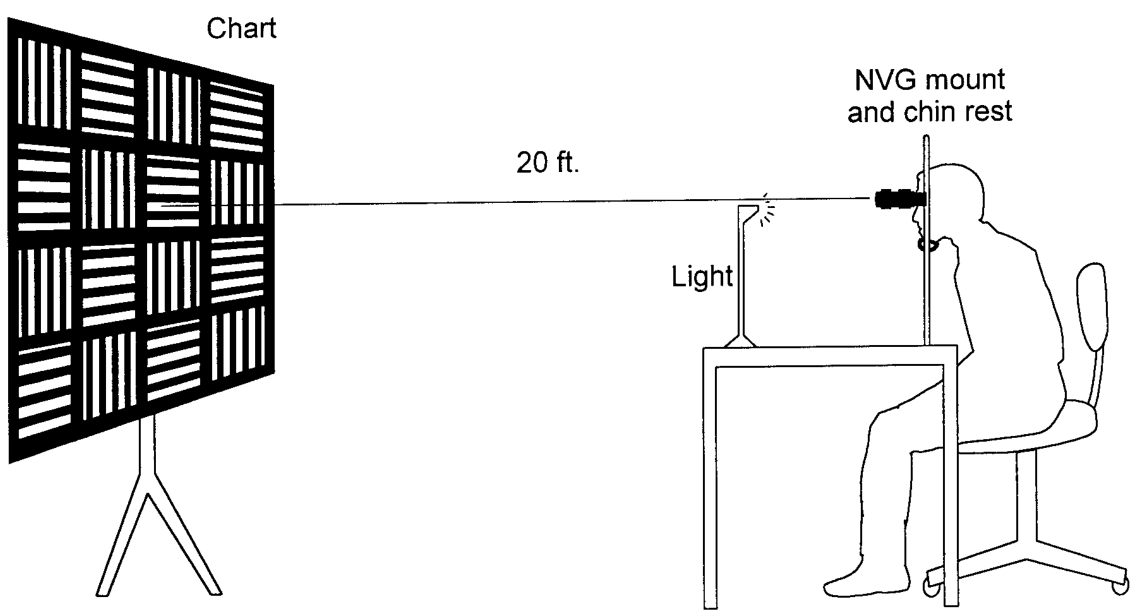

Figure 7. The experimental set-up. Subjects sat in a chair with a chin rest and NVGs. The light source was mounted to the table and 20 ft away were the visual performance charts.

NVG Resolution Chart. The procedure for determining the NVG-aided VA using the charts was taken from DeVilbiss and Antonio (1994). Each subject read the resolution patterns from left to right and top to bottom under each of the four possible chart orientations. Thus, each pattern was viewed four times (two vertically and two horizontally). Subjects indicated whether a pattern was vertical, horizontal, or could not be resolved. The subjects were specifically informed not to guess at a pattern's orientation. If subjects were not 100% confident of the orientation they were to inform the recorder that they could not tell the direction of the grating. Also, they were directed to maintain a steady pace of pattern reporting. This ensured that the subjects would not spend more than a second or two attempting to discriminate the grating's orientation. The number of correct vertical and horizontal responses was totaled, and VA values were determined using a 75% correct criterion. Psychophysical measures routinely use a probability value to define the level of recognition of a target. For example, in using this NVG Resolution chart, if a subject correctly identified the 20/55 pattern 100% of the time (8 of 8), the 20/50 pattern 75% of the time (6 of 8), and the 20/45 pattern 62.5% of the time (5 of 8), the subject's VA would be assessed as 20/50. If no resolution could be resolved, it was scored as 20/95. See Appendix B for a sample of the data recording sheet.

USAF 1951 Tri-bar Chart. The procedure for testing this chart required the subject to state the smallest row and column that they could see. Subjects had to identify three vertical and three horizontal bars in each element. It was stressed to the subjects that they must clearly identify the three black bars and two white spaces in each direction

for the pattern to be resolvable. See Appendix C for a sample of the data recording sheet and scoring computations.

NVG Contrast Sensitivity Chart. The procedures used in this test were similar to those used with the NVG Resolution charts. The order in which the subjects viewed the NVG CS charts was completely randomized. The subject read the vertical or horizontal gratings from left to right and top to bottom for each of the four orientations. The same 75% criteria was used to formulate the particular spatial frequency's contrast threshold as the NVG Resolution chart. If no contrast could be resolved the subject was scored at 100. See Appendix D for a sample of the data recording sheet.

RESULTS

Appendix E contains the collected VA scores for the two different charts and the contrast limits for the three different spatial frequency charts. It is these data that all analyses and interpretation were based upon. This section will examine the statistics and present the results. The in-depth discussion and interpretation of the results will be accomplished in the next section, the discussion section.

Contrast Sensitivity

Table 2 lists the spatial frequencies and light condition means and standard deviations. Inspecting these data reveals the size of the variability in contrasts limits in the 12 cpd chart: 1) standard deviations were 10.52 at the baseline condition; 2) 29.87 at the green light condition; and 3) 19.66 at the red light condition.

Table 2

NVG-aided Contrast Sensitivity Means and Standard Deviations

	Baseline	Green Light	Red Light
12 cpd Chart			
Mean	35.69	59.70	87.48
Standard Deviation	10.52	29.87	19.66
6 cpd Chart			
Mean	9.48	11.13	14.96
Standard Deviation	2.94	5.31	7.04
3 cpd Chart			
Mean	7.00	6.66	8.84
Standard Deviation	1.97	2.27	3.47

The two lower frequency charts, 3 and 6 cpd, produced more consistent contrast limits between the subjects. Those chart's standard deviations ranged from approximately 3 - 7 for the 6 cpd chart and 2 - 3.5 for the 3 cpd chart.

A within subjects ANOVA (Table 3) revealed significant main effects of spatial frequency, $F\ (2, 38) = 213.57$, $p < .001$, light condition, $F\ (2, 38) = 64.0$, $p < .001$, and a significant interaction between spatial frequency and light condition, $F\ (4, 38) = 46.86$, $p < .001$. The experimental design of this research used a significance level of .05, however, these effects were also significant at the .01 level. The analyses rejected two of the three null hypotheses. The two null hypotheses were: 1) the three CS charts will show equal percentage degradation - rejected; and 2) the effect of the different light conditions will be equal - rejected.

Table 3

Analysis of Variance for NVG Contrast Sensitivity Charts

Source	df	SS	F-value	p-value
Spatial Frequency	2	105,744.3	213.57	< .001
Light	2	11,728.4	64.0	< .001
Interaction	4	15,517.1	46.86	< .001
Spat Freq x Sbjct	38	9,407.5	(247.56)	
Light x Sbjct	38	3,481.6	(91.62)	
Interaction x Sbjct	76	6,291.4	(82.78)	

Note. df = degrees of freedom; SS = sums of squares. Values enclosed in parentheses represent mean square errors.

An ANOVA of simple effects was conducted to further breakdown the effect of light on each of the different spatial frequencies (see Table 4). Again, the effect of the light conditions on each spatial frequency chart were significant down to the .01 level.

Table 4

Analysis of Variance of NVG CS Charts - Simple Effects

Source	df	SS	f-value	p-value
Light @ 12 cpd	2	26,874.7	54.76	< .001
Light @ 6 cpd	2	315.7	17.11	< .001
Light @ 3 cpd	2	55.1	10.78	< .001
Light @ 12 cpd x subjects	38	9,325.3	(245.4)	
Light @ 6 cpd x subjects	38	350.5	(9.22)	
Light @ 3 cpd x subjects	38	97.2	(2.56)	

Note. df = degrees of freedom; SS = sums of squares. Values enclosed in parentheses represent mean square errors.

A comparison of means was accomplished to specifically determine which light condition in each NVG CS chart was statistically different. Both Tukey's test and Dunnett's test revealed the same statistical differences. The change in contrast threshold from baseline to green and from baseline to red was significant only in the 12 cpd chart. The 6 cpd and 3 cpd charts only showed statistical significance from the change in baseline to the red light condition.

Visual Acuity

Table 5 lists the means and standard deviation of the different treatment combinations of the VA charts and light conditions. Simple observation of the two VA chart's means at every light condition reveals almost identical means.

Table 5

NVG-aided Visual Acuity Means and Standard Deviations

	Baseline	Green Light	Red Light
NVG Chart			
Mean	49.0	55.0	65.25
Standard Deviation	4.47	4.29	11.30
1951 Tri-bar Chart			
Mean	48.50	55.45	65.43
Standard Deviation	4.23	5.74	8.56

A within subjects ANOVA (Table 6) revealed that the only statistically significant effect was the light, $\underline{F}\ (2, 38) = 87.52$, $\underline{p} < .001$. The main effect of the chart and the interaction of the chart and the light effect were not significant. In fact, the two assessment charts were very similar, $\underline{F}\ (1, 19) = .05$, $\underline{p} = .971$. The null hypothesis was that the two VA charts would produce equal VA scores. A p-value this high indicates with only 3% confidence the null hypothesis could be rejected.

Table 6

Analysis of Variance for NVG Visual Acuity Charts

Source	df	SS	F-value	p-value
Chart	1	0.05	.001	.971
Light	2	5,594.4	87.52	<.001
Interaction	2	4.9	2.42	.894
Chart x Sbjct	19	728.8	(38.36)	
Light x Sbjct	38	1,214.5	(31.96)	
Interactions x Sbjct	38	821.4	(21.62)	

Note. df = degrees of freedom; SS = sums of squares. Values enclosed in parentheses represent mean square errors.

There was some concern over the homogeneity of the subjects because six of the twenty subjects were pilots and three of those pilots had NVG experience. The reason for concern was that those subjects may have had better visual skills than the other 14 subjects. Consequently, this would result in a non-homogeneous sample. The pilot subjects and the NVG experienced subjects (see Appendix F) performed better than the average of the remaining subjects in the VA and CS assessments. However, analyses of the three different groups, six pilots, three NVG experienced, and the 14 remaining subjects, revealed no statistical difference between the group's variances at the five baseline conditions. Statistical analyses, using three pair-wise t-tests, was then conducted to determine if the means of the different groups were statistically significant. The three groups were found to be statistically similar at the baseline VA conditions (both NVG Resolution chart and Tri-bar chart). The three groups were also equivalent in the 6 and 3

cpd chart, baseline condition. However, the NVG experienced group did perform significantly better than the 14 subjects that did not have either flying or NVG experience at the baseline condition in the 12 cpd chart. There was no significant difference between the flying and NVG experienced groups at any of the baseline conditions. The comparison of the pilot subjects versus the subjects without flying or NVG experience revealed no significant difference in any of the five baseline conditions. Because the NVG experienced group was a small percentage of the total number of subjects (15%) and the statistical tests that were conducted it was concluded that the assumption of sample homogeneity was met.

DISCUSSION

Contrast Sensitivity

CS is a Useful Assessment Tool. The primary objective of this study was to demonstrate that using CS to measure NVG performance under incompatible cockpit light conditions could be a useful tool. This research clearly demonstrated that CS was a viable assessment tool of NVG visual performance under degraded visual scenes. Both the spatial frequency and the effect of degrading lights, as well as their interaction, proved to be statistically significant. The type of chart presented to the subjects and the given light conditions both significantly affected the visual performance of the subjects on the highest spatial frequency chart. The two lower spatial frequency charts significantly affected the visual performance of the subjects at only the red light condition, not the green light condition.

These data provided an initial quantification of the contrast thresholds for 3, 6, and 12 cpd under starlight conditions using a modified Class B goggle. Incompatible light is a very serious problem to the NVG user. Quantifying the contrast threshold limits at starlight (the defined military specification illumination level) is one of the first steps in researching the compatibility of the modified Class B goggle interfacing with today's cockpits.

Table 7 lists the percent-change from baseline for the two VA charts and the three CS charts assessed at the green and red light conditions.

Table 7

Percentage Change from Baseline of the VA and CS Charts

	NVG Chart	Tri-bar Chart	12 cpd	6 cpd	3 cpd
Green Light	11.9	12.5	40.2	14.8	0
Red Light	24.9	25.9	59.2	36.6	20.9

From baseline to the green light condition, the VA charts revealed a 11-12% drop in acuity and the 12 and 6 cpd charts revealed a 40 and 15% drop in contrast, respectively. In the red light condition, the VA charts revealed a 25-26% drop in acuity while the 6 and 3 cpd charts revealed 36 and 21% drop in contrast, respectively.

This does not imply that, due to the increased percentage in degraded visual scene, CS is a better visual assessment tool than VA. It merely demonstrates that CS can be used as a supplementary assessment tool. Combined with VA tests, CS may present more of an accurate visual degradation assessment. As Rabin (1993) stated earlier, "...acuity provides only the limit of resolution, while contrast sensitivity can provide a more comprehensive index of visual function over a range of stimulus sizes" (p. 706). CS and VA measure different aspects of the visual system. This study demonstrated that CS can discriminate a change in a visual scene. NVG CS charts assessed a loss in visual performance. The performance decrement was determined by the choice of spatial frequency and the contrast levels used in the assessment procedure. Unlike VA assessments which produce one acuity value, CS is a more complicated measure. Simply assessing one spatial frequency does not sufficiently contribute towards understanding the entire spectrum of the visual scene. Multiple spatial frequencies must be examined.

<u>Comparison between Subjects.</u> Earlier it was noted by Hawkins (1987) that two individuals could both have 20/20 vision but have very different abilities in complex visual environments. The standard vision test for pilots is VA. The following examples show that normal VA does not necessarily equate to normal CS. There are numerous examples of subjects that had the same unaided VA and the same baseline NVG-aided VA, but had very different CS scores. Appendix E has the complete list of all of the subject's data at all test conditions. Table 8 has one of these cases; a comparison between subjects 19 and 22.

Table 8

<u>Same Baseline VA but Different NVG-aided CS</u>

		NVG VA NVG 20/xx VA			NVG VA Tri-bar VA 20/xx			NVG CS 12 cpd			NVG CS 6 cpd			NVG CS 3 cpd		
Sbjct	Tri-bar bl VA	bline	grn	red	bline	grn	red	bline	grn	red	bline	grn	red	bline	grn	red
19	17.9	50	50	60	45	50.6	57	32	49.5	89	11	10.8	16	8	6.6	8
22	17.9	50	60	75	45	56.8	64	42	100	100	11	11.6	18	9.9	11.6	12
AVE	18.9	49	55	65	48	55.5	65	36	59.7	87	9.5	11.1	15	7	6.66	9

<u>Note.</u> Sbjct = subject; bl = baseline (unaided); grn = green; NVG VA = NVG Resolution chart; Tri-bar = USAF 1951 Tri-bar chart; AVE = total sample average of the 20 subjects. Values in this table are rounded-up from the values found in Appendix E.

These two subjects had the same unaided VA and the same baseline NVG-aided VA on both VA charts. But close examination of their CS scores revealed that subject 22 needed higher contrast in eight of the nine CS charts than subject 19. Subject 22 averaged 10% higher CS scores then subject 19. Also, subject 22's 12 cpd CS was worse than the total average and did not resolve any of the contrast patterns in the green and red

condition - despite very good VA and NVG-aided VA. Subject 22 had flying experience. Through the years of flight physical examinations this subject has had only VA tests. Other sets of subjects that had the same VA scores but noticeably different CS scores were subjects 9 vs. 18, 5 vs. 17, and 14 vs. 16.

Close examination of the data also revealed that five of the subjects consistently had lower than average CS thresholds (subjects 5, 6, 9, 18, & 20). Subjects 5, 6, and 9 especially had good CS, they often were 1 standard deviation below average. These individuals possess very good CS that would not normally be discovered in routine vision tests. More importantly, those subjects with average VA but below average CS would not be discovered in visual performance assessments. For example, the following subjects in Table 9 had, at worst, average unaided VA and NVG-aided VA. However, they had worse than average CS (1 standard deviation or greater) on at least one of the light/spatial frequency conditions. The subject's contrast levels that are highlighted in Table 9 are those levels that exceeded 1 standard deviation.

The subjects in Table 9 had NVG-aided CS which displayed a reduced ability to see contrast at the high spatial frequency, 12 cpd chart, compared to the average in all but one case. In the green and red light conditions, most of these subjects could not see any contrast levels on the high frequency chart. On the 6 and 3 cpd charts many of these subjects had greater than the mean contrast limit at all light conditions. Subject 13 had especially poor CS. At every condition, Subject 13 was greater than 1 standard deviation greater than the average contrast threshold. In the red light condition Subject 13 scored the highest contrast level of all the subjects.

Table 9

Good Baseline NVG-aided VA but Poor NVG-aided CS

	Tri-bar	NVG VA NVG 20/xx VA			NVG VA Tri-bar VA 20/xx			NVG CS 12 cpd			NVG CS 6 cpd			NVG CS 3 cpd		
Sbjct	bl VA	bline	grn	red	bline	grn	red	bline	grn	red	bline	grn	red	bline	grn	red
7	17.9	55	60	75	57	71.6	80	**55**	88.8	**100**	11	10.8	18	7.3	6.6	12
13	15.9	50	65	95	51	56.8	72	**50**	**100**	**100**	**16**	**28**	**39**	**12**	**11.6**	**15**
16	17.9	50	55	70	45	50.6	72	**50**	80.7	81	**18**	**21**	21	**9.9**	**9.9**	12
17	20.1	50	55	75	51	63.8	72	44	**100**	**100**	7.6	10.8	18	6.6	6.6	8
21	15.9	50	55	75	45	56.8	64	**50**	**100**	**100**	8.5	7.6	16	6.6	4.7	8
22	17.9	50	60	75	45	56.8	64	42	**100**	**100**	11	11.6	18	**9.9**	**11.6**	12
AVE	18.9	49	55	65	48	55.5	65	36	59.7	87	9.5	11.1	15	7	6.66	9

Note. Sbjct = subject; bl = baseline (unaided); grn = green; NVG VA = NVG Resolution chart; Tri-bar = USAF 1951 Tri-bar chart; AVE = total sample average of the 20 subjects. Highlighted values are 1 standard deviation or greater. Values in this table are rounded-up from the values found in Appendix E.

Subject 13 could only resolve the 6 cpd chart at 39% contrast (average was 14.9%) and on the 3 cpd chart this subject could only resolve it at 15.3% contrast (average was 8.8%). Subject 13 also had very poor NVG-aided VA at the red light condition. Individuals similar to these subjects would probably pass any standard VA test. Unfortunately their lack of NVG-aided CS and their poor performance under a severely degraded visual scene would not be discovered in a standard visual examination. It may be individuals such as these who later find it difficult to accomplish tasks in complex visual environments, like flying at night or wearing NVGs. Kruk et al. (1981) concluded their research with this same point, pilots having equal VA may not have similar CS. "Thus, the Snellen test would be expected to let through an occasional pilot with very low

contrast sensitivity...the potential problem could be avoided by adding a contrast test to pilot screening" (Kruk, et al., 1981, p. 459).

NVG CS Chart Design. The range of contrast levels used, from lowest to highest, was sufficient for all subjects at the baseline condition. None of the subjects could see all of the contrast patterns. The 12 cpd chart was especially appropriate for baseline, starlight conditions because it is approximately equivalent to a Snellen acuity of 20/50. This was almost exactly the average of the baseline NVG-aided VA. The two VA charts had contrast levels of 50 and 70%. On the NVG CS chart, a 20/50 equivalent spatial frequency, the minimum average contrast was 36%. This shows a drop of 14% in contrast on the NVG CS chart from the NVG Resolution Chart. This demonstrated that the contrast could drop 14% and the acuity of 20/50 be maintained.

The green light condition degraded NVG-aided VA to an average of 20/55 and consequently, the minimum contrast limit increased to 59.7% on the 12 cpd NVG CS chart. Five of the subjects could not make out any of the patterns on the 12 cpd chart. For the severely degraded visual scene, the red light condition, the 12 cpd chart was not appropriate to accurately assess the subjects' visual performance. Thirteen of the subjects could not see any of the patterns. This was because the average NVG-aided VA degraded to 20/65 (approximately 9 cpd) and the subjects could not see such a high spatial frequency of 12 cpd, regardless of the contrast level.

The 6 cpd degree chart was approximately equivalent to 20/100 Snellen VA. This was an effective spatial frequency for detecting degradation due to incompatible light at

only the red light condition. It did not reveal a degraded visual scene in the green light condition.

The 3 cpd chart was very easy for the subjects to discriminate and some subjects reported contrast levels as low as 3%. This chart only detected a statistically significant finding of degradation to the red light condition. It did not reveal a degraded visual scene in the green light condition. A strange and unexplained phenomena in using NVGs is that occasionally, even in the presence of a slightly incompatible light, the visual scene improves. This has been reported by NVG pilots (J. C. Antonio, personal communication, June 26, 1996). The data revealed that this occurred in the green light condition at 3 cpd. Seven subjects improved their CS, eight subjects maintained the same CS as their baseline, and only five subjects showed degraded CS at the green light condition. How an incompatible light can actually improve the visual scene is an area in need of further research.

Contrast Sensitivity Function. Figure 8 follows the standard shape of a CSF, the relationship of contrast sensitivity (the reciprocal of contrast threshold) and spatial frequency. At lower spatial frequencies very little contrast is needed to discriminate between the orientation of the chosen gratings. The 3 cpd chart allowed some subjects to see the correct orientation of the square-wave grating down to 3% contrast (baseline average was 7.0%). On the 12 cpd chart, the lowest contrast level reported was 18.3% (baseline average was 35.7%). Figure 8 shows that the red light condition, the most severe degradation, created the highest contrast values to discriminate the gratings at all spatial frequencies. At the green light condition, the CSF depicts the slight improvement

in the 3 cpd chart from baseline and then the drop below baseline at the 6 and 12 cpd charts.

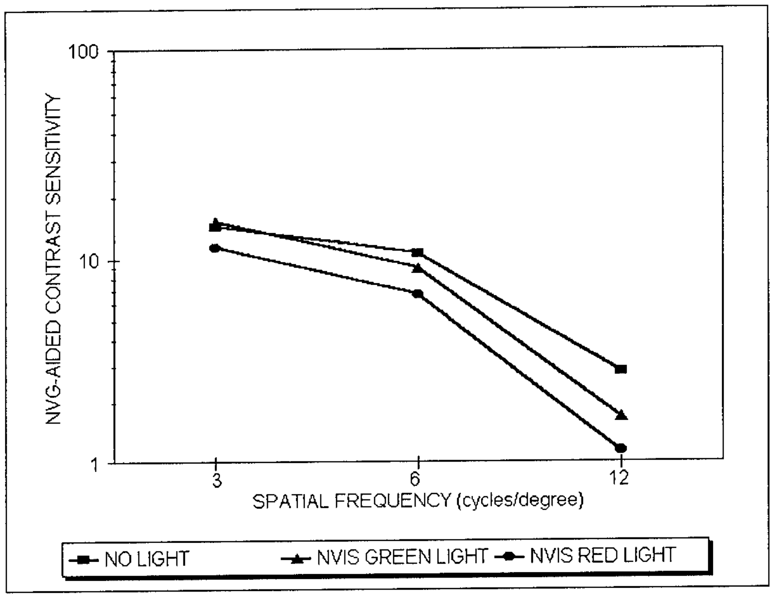

Figure 8. The contrast sensitivity function (CSF) of the three light conditions.

Ginsburg et al. (1983) found that the higher spatial frequencies, 8, 16, and 24 cpd, correlated with detection performance better than the lower frequencies. Rabin (1995) and Rabin and McLean (1996) stressed that the steep portion of the CSF as being most vulnerable to a degraded visual scene. This is due to a small change in VA (cpd equivalent, x-axis) resulting in a large change in contrast sensitivity (y-axis). This is clearly demonstrated in the 12 cpd chart at the green light condition. The majority of the subjects could still discriminate the high spatial frequency, NVG-aided VA only dropped 11%. However, their contrast dropped 40% on the 12 cpd chart, 14% on the 6 cpd chart, and showed improvement on the lowest spatial frequency, the 3 cpd chart. This also

follows what Rabin (1993) stated, that higher spatial frequencies showed more degradation than the lower spatial frequencies.

Recommendations. The strongest recommendation is that examinations of pilot's vision who routinely operate in complex visual environments, such as NVG operations, be expanded to include NVG-aided CS and NVG-aided VA assessments. The examples of subjects that had normal unaided VA but abnormal NVG-aided VA and CS should serve notice that much more needs to be understood about human vision in the arena of NVG flying. The inherent risks of pilots in the NVG flying environment ought to bring about changes in the selection process of those pilots. Ginsburg et al. (1982) concluded his research questioning the current standard vision tests for individuals working in complex visual environments. Accomplishing additional eye exams, such as measuring CS and/or NVG-aided CS and VA, on NVG pilots would be one important step towards reducing human factor caused aircraft accidents.

Future studies involving CS should use an additional spatial frequency. The 3, 6, and 12 cpd charts were sufficient but not optimal. The incompatible light conditions studied could have been better examined if a 9 cpd chart had been developed. The 9 cpd is approximately equivalent to 20/67 Snellen VA and would have been able to provide a better contrast limit of the red light condition when the 12 cpd became too high of a spatial frequency. The red light condition average NVG-aided VA was 20/65, showing the 9 cpd chart would have been a better choice. The 0.05 log unit decrease in contrast levels worked well but for lower spatial frequencies may have been too small a change to easily and consistently be seen by the subjects. The 3 and 6 cpd charts had fewer clean

threshold breaks in their data; meaning subjects were inconsistent in correctly naming the square-wave patterns near their threshold level.

Much of cockpit light compatibility testing occurs in the field. It would be very time consuming and awkward to carry three large, NVG CS charts. It would be more effective to develop one CS chart based on the Vistech CS chart, that was described earlier. The chart would have four rows of spatial frequencies (3, 6, 9, & 12 cpd) and each spatial frequency would have nine columns of decreasing contrast. The collected data would produce a four-point CSF at the particular experimental condition.

Visual Acuity

The NVG VA Charts are equivalent. The null hypothesis was that both NVG VA charts would produce equal VA scores - these findings confirmed this hypothesis. There was very little evidence to suggest that the null hypothesis should not be accepted. Despite numerous reports by the subjects that the USAF 1951 Tri-bar chart was more subjective, it proved to be statistically equivalent in assessing NVG-aided VA. One subject even stated that they felt that they could "game" the Tri-bar chart. What this meant was that based upon knowledge of their previous performance, regardless of the test condition, the subject could more subjectively state their minimum resolvable pattern. This researcher initially felt that the Tri-bar chart would prove less accurate as an assessment tool and show more variability both between and within subjects. That was based on research conducted prior to this experiment (Reising et al, 1995) and subject comments made during the experiment. However, only the light condition proved to be statistically significant. The light effect was significant from baseline to the green light

and from baseline to the red light. In other words, the light statistically affected the NVG-aided VA scores of the subjects.

The results of this research show that either chart would be an appropriate assessment tool to test NVG-aided VA. The question may remain though, which chart should be used in what research conditions? With a small and inexperienced group of subjects, the NVG Resolution chart may be the best choice. The NVG Resolution chart would be the preferred tool in this case because the inexperienced subjects would produce more data from the multiple orientations of viewing the chart. This would give the researcher a more comfortable feeling about the validity of the collected data. However, the NVG Resolution chart is much more time consuming. If time is a factor, then the Tri-bar chart is the obvious choice. Also, if a subject is experienced and familiar with the Tri-bar chart it would be the proper choice of assessment.

Slight Differences Between the Charts. The two NVG VA charts are slightly different, which makes the statistically similar significance of the charts even more surprising. The NVG Resolution chart is a 50% contrast chart and the USAF 1951 Tri-bar chart is a 70% contrast chart. The subjectivity of the Tri-bar chart may have been compensated in the 20% contrast difference. Also, the Tri-bar chart consistently has 11% change in element patterns. The 20/45.1 to 20/50.6 is the same amount of change as 20/63.8 to 20/71.6 patterns. The NVG Resolution chart changes in the difference between patterns. It continually has a decreasing difference between VA patterns from an 11% change at the 20/40 to 20/45 pattern to a 6% change at the 20/75 to 20/80 pattern.

Earlier Boff and Lincoln (1988) had noted the lack of correlation between VA assessments. They pointed out that the differences in VA measurements were due to differences in the confidence in judgments by the subjects and in the criteria of reporting what was being viewed by the subjects. In this study the subjects were instructed to use 100% confidence in reporting the pattern orientation on both the NVG Resolution chart and on the Tri-bar chart. However, in the scoring of the NVG Resolution chart a 75% correct criteria was applied in determining the final VA score. The Tri-bar chart score was the actual 100% reported pattern stated by the subject. These slightly different scoring criteria could have produced varying results between the subjects, yet they did not.

Another significant finding was the greater variability under the red light condition that the NVG Resolution chart, 11.30 standard deviation, displayed compared to the USAF 1951 Tri-bar chart, 8.56 standard deviation. Possibly the improved contrast of the Tri-bar chart played a larger role in the red light condition. Another possible explanation may be due to experimental run-order. Though completely randomized, during two-thirds of the trials another light condition was presented prior to the red light condition. Consequently, with the more severe degradation the subjects used this prior knowledge of their past Tri-bar chart reading as a known reference for future visual assessments. The NVG Resolution chart has too many patterns and unknown orientations for the subjects to attempt to remember their previous visual performances. As it was pointed out earlier, it is not possible for individuals to physiologically quantify their own visual performance (DeVilbiss & Antonio, 1994). The Tri-bar chart, however, enables

subjects to always have a known starting point to base other observations on and this may help an experienced user of the chart.

Recommendations. The concept of unchanged VA accompanied with a noticeable change in apparent contrast is what stimulated this research project to investigate CS as a visual assessment tool. CS combined with VA is an optimum method to evaluate the total visual performance decrement. The military specifications state that a light is declared incompatible if VA is affected. This limited visual performance standard may allow a so-called compatible cockpit light to pass the VA test. However, it may actually be an incompatible light because it degrades the environment's contrast.

A slight change in methodology is recommended for future incompatible cockpit light and CS and VA comparisons. For this research a pilot study produced the intensity of light needed for slight and severe degradation of the visual scene. It is suggested that both CS and VA assessments be taken while making small incremental changes in the intensity of an incompatible light. This methodology may reveal a specific breaking point where one of the visual assessment measures fail to notice a change in visual performance while another measure discriminates the loss in performance. This method would provide data that could ensure that a compatibility test passes both CS and VA standards.

The Modified Class B NVG

Military specifications state that an NVIS Green B light must be at 0.1 fL and at a NVIS Radiance of 1.7×10^{-10}. The NVIS Green B used in this research was at an unrealistic cockpit intensity of 259 fL and 4×10^{-7} NRb. That is a light intensity of 2,590

times what is accepted and what is realistically ever seen - and it only slightly degraded the visual scene. The NVIS Green B used had 60% of its energy at the 545 nm spectral region. This is the spot where 1% of 545 nm is allowed into the NVG for HUD readability. The Lockheed MC-130H Talon II, the most NVIS Green A/B illuminated cockpit in the Air Force, uses NVIS Green lights as caution and warning indicators. These specific types of warning indicators are allowed by military specifications to be at 15 fL and a NRb of 1.4×10^{-7}. This research simulated 17 caution/warning indicators and three times the NVIS Radiance, all in the FOV of the NVG, and only degraded the visual scene 11 - 12% in NVG VA. Clearly, this demonstrates that the modified Class B NVG meets the specifications of the current Class B NVG.

Operational Relevancy

A major concern of this research is what information it can provide to the operational pilot. There is the tendency to only focus on the severely degraded visual scene. All of the subjects, when presented with the red light condition (severe degradation), immediately commented on how difficult it was for them to see. In this severely degraded visual scene, the subjects could not physiologically quantify their performance but they immediately recognized a very poor visual environment. Consequently, if this type of visual degradation is encountered while flying, the pilot would transition to instrument flying and climb away from the terrain to ensure safety.

Greater concern is for the slight degradation that the green light condition produced. As DeVilbiss and Antonio (1994) stressed, reduced VA can frequently go undetected. Berkley (1992) stated that an incompatible cockpit light is "...imperceptible

to the pilot" because the NVG's ABC feature maintains the same visual scene to the pilot despite the presence of a light in the FOV (p. 4). All of the subjects commented on the presence of a light source in their FOV but few stated an obvious degraded visual environment. The insidious loss of the visual environment is much more dangerous then an obvious and dramatic loss of a visual scene. This is why an incompatible cockpit light is "...potentially the most serious factor in NVG operational capability and safety!" (Berkley, 1992, p. 4). This lack of recognition of the degraded visual scene, though only slight degradation, is what increases the potential for human error. CS degraded up to 40%. VA degraded approximately 12%. The combined loss of contrast and resolution may result in limited depth perception. What is normally seen at the 1 mile point may not become visible until less then three-quarters of a mile. If unaware of the degraded visual environment, this may result in a delayed reaction over an approaching ridgeline on a low level mission. If a pilot is aware of the degraded visual scene the proper action to take would be to increase the altitude over the terrain - providing a larger margin for error.

The slight degradation of a visual scene by an incompatible cockpit light reduces VA and significantly affects higher spatial frequency objects. Flying at night does not require the skills of picking out high contrast black letters. Flying at night does require the visual skills of seeing high spatial frequencies at low contrast conditions. Degraded acuity combined with poor contrast can lead to disaster. Pilots must be aware of the limitations that their NVG capabilities create. These visual limitations require the situational awareness abilities of the pilot to equal the technological advances of the airplane.

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APPENDIX A

INSTRUCTIONS/CONSENT FORM

INSTRUCTIONS/CONSENT FORM

Thank you for volunteering for this study. You are about to participate in a Night Vision Goggle (NVG) visual performance study. The purpose of this study is to compare assessment techniques under a variety of conditions. The results of this study will be used to aid in the further research of NVGs and in the design of compatible cockpit lights. Your participation in this study is purely voluntary and individual data collected will remain completely anonymous. If at any time you feel uncomfortable with the research procedures you may terminate the experiment and be excused.

The chair you are sitting in is where you will be seated for the entire experiment. There will be no need to move unless you feel you need a break and would like to stretch your legs. The chin-rest will be adjusted to allow you to comfortably look through the NVGs and view the charts on the other end of the eye lane.

During this study you will view two different type of charts. On one chart you will be asked to report either horizontal or vertical patterns viewed on a chart. Please keep a steady pace of pattern reporting. Some of the patterns may become difficult to see, if you are not 100% sure of the pattern please state, "can't tell". This technique will ensure the data collection moves along at a steady pace and keeps you from possibly moving your eyes all over the chart to try and re-focus on a particular pattern or attempting to guess the pattern based on previous patterns. Another chart assessment will simply require you to inform the recorder of the smallest row and column number that you can perceive. You must be able to clearly see three black bars and two white spaces in each direction in order for it to qualify as a resolvable pattern.

There are no hazards involved in this study. The NVGs have been approved by flight surgeons, and pose no risk of causing any damage to your eyes. This study will take approximately one hour to complete. If you have any questions during the course of the experiment, please ask. Again, thank you for volunteering for this study.

Printed name ____

Signature ____ Date __________

APPENDIX B

NVG RESOLUTION CHART DATA FORM

LOW RANGE NVG VISUAL ACUITY SCORE CARD

NAME ______________________ CONDITION ______________________

DATE ______________________ GOGGLE ______________________

ACTUAL VALUES:

Orientation 1

H	V	H	H
V	H	V	H
V	H	V	V
H	V	H	V

Orientation 2

V	V	H	H
V	H	H	V
H	V	V	H
V	H	H	V

Orientation 3

V	H	V	H
V	V	H	V
H	V	H	V
H	H	V	H

Orientation 4

V	H	H	V
H	V	V	H
V	H	H	V
H	H	V	V

SUBJECT RESPONSE:

Orientation ___

Orientation ___

Orientation ___

Orientation ___

20/xx	1			2			3			4			
50	(1,2)	V		(3,1)	H		(4,3)	V		(2,4)	H		
55	(3,2)	H		(3,3)	V		(2,3)	H		(2,2)	V		
60	(2,3)	V		(2,2)	H		(3,2)	V		(3,3)	H		
60	(4,1)	H		(4,4)	V		(1,4)	H		(1,1)	V		
65	(3,4)	V		(1,3)	H		(2,1)	V		(4,2)	H		
65	(4,3)	H		(2,4)	V		(1,2)	H		(3,1)	V		
70	(1,1)	H		(4,1)	V		(4,4)	H		(1,4)	V		
70	(4,2)	V		(3,4)	H		(1,3)	V		(2,1)	H		
75	(2,4)	H		(1,2)	V		(3,1)	H		(4,3)	V		
75	(4,4)	V		(1,4)	H		(1,1)	V		(4,1)	H		
80	(1,4)	H		(1,1)	V		(4,1)	H		(4,4)	V		
80	(2,1)	V		(4,2)	H		(3,4)	V		(1,3)	H		
85	(3,3)	V		(2,3)	H		(2,2)	V		(3,2)	H		
85	(3,1)	V		(4,3)	H		(2,4)	V		(1,2)	H		
90	(2,2)	H		(3,2)	V		(3,3)	H		(2,3)	V		
90	(1,3)	H		(2,1)	V		(4,2)	H		(3,4)	V		

APPENDIX C

USAF 1951 TRI-BAR CHART

USAF 1951 TRI-BAR CHART

SUBJECT ____________________________

CONDITION _________________________

ELEMENT/GROUP ___________________

VA _______________

SAMPLE CALCULATION

Given: element and group number (-3/4) = unit (cycle) width in mm (size of object)
= 5.657 mm

viewing distance is 20 ft = 6096 mm

visual angle formula: $\tan \theta$ = object size/object distance
θ = arctan object size/object distance
θ = arctan 5.657/6096
θ = 0.053 degrees = 18.868 cycles/degree

cycles per degree conversion to Snellen acuity: 30 cpd = 20/20
xx = 20 * (30 * θ)
xx = 20 * (30 * 0.053)
xx = 31.8

Therefore: USAF 1951 Tri-bar chart element & group of -3/4 is 20/31.8 VA

APPENDIX D

NVG-AIDED CONSTRAST SENSITIVITY DATA FORMS

NVG-AIDED CONTRAST SENSITIVITY DATA SHEET - 12 CPD

NAME ____________________ **NVG**____________________
CONDITION____

ACTUAL VALUES:

Orientation 1	Orientation 2	Orientation 3	Orientation 4
H V H H	V V H H	V H V H	V H H V
V H V H	V H H V	V V H V	H V V H
V H V V	H V V H	H V H V	V H H V
H V H V	V H H V	H H V H	H H V V

SUBJECT RESPONSE: CS = ______

Orientation ___	Orientation ___	Orientation ___	Orientation ___

SCORING:

CONT	Orientation 1	Orientation 2	Orientation 3	Orientation 4	Total Correct
88.8	(1,3) H	(2,1) V	(4,2) H	(3,4) V	___
80.7	(2,3) V	(2,2) H	(3,2) V	(3,3) H	___
69.1	(4,2) V	(3,4) H	(1,3) V	(2,1) H	___
63.7	(3,4) V	(1,3) H	(2,1) V	(4,2) H	___
55.2	(2,1) V	(4,2) H	(3,4) V	(1,3) H	___
49.5	(1,1) H	(4,1) V	(4,4) H	(1,4) V	___
44.4	(3,2) H	(3,3) V	(2,3) H	(2,2) V	___
42.3	(4,1) H	(4,4) V	(1,4) H	(1,1) V	___
35.3	(4,4) V	(1,4) H	(1,1) V	(4,1) H	___
31.5	(1,2) V	(3,1) H	(4,3) V	(2,4) H	___
28.2	(2,4) H	(1,2) V	(3,1) H	(4,3) V	___
26.1	(4,3) H	(2,4) V	(1,2) H	(3,1) V	___
22.9	(3,1) V	(4,3) H	(2,4) V	(1,2) H	___
18.3	(2,2) H	(3,2) V	(3,3) H	(2,3) V	___
17.4	(1,4) H	(1,1) V	(4,1) H	(4,4) V	___
16.8	(3,3) V	(2,3) H	(2,2) V	(3,2) H	___

NVG-AIDED CONTRAST SENSITIVITY DATA SHEET - 6 CPD

NAME ______________________ **NVG**____________________
CONDITION____

ACTUAL VALUES:

Orientation 1	Orientation 2	Orientation 3	Orientation 4
H V H H	V V H H	V H V H	V H H V
V H V H	V H H V	V V H V	H V V H
V H V V	H V V H	H V H V	V H H V
H V H V	V H H V	H H V H	H H V V

SUBJECT RESPONSE: CS = ______

Orientation __	Orientation __	Orientation __	Orientation __

SCORING:

CONT	Orientation 1	Orientation 2	Orientation 3	Orientation 4	Total Correct
44	(4,2) V	(3,4) H	(1,3) V	(2,1) H	___
39	(3,4) V	(1,3) H	(2,1) V	(4,2) H	___
31.8	(2,1) V	(4,2) H	(3,4) V	(1,3) H	___
28	(1,1) H	(4,1) V	(4,4) H	(1,4) V	___
25	(3,2) H	(3,3) V	(2,3) H	(2,2) V	___
21	(4,1) H	(4,4) V	(1,4) H	(1,1) V	___
17.9	(4,4) V	(1,4) H	(1,1) V	(4,1) H	___
16.2	(1,2) V	(3,1) H	(4,3) V	(2,4) H	___
14.3	(2,4) H	(1,2) V	(3,1) H	(4,3) V	___
12	(4,3) H	(2,4) V	(1,2) H	(3,1) V	___
11.6	(3,1) V	(4,3) H	(2,4) V	(1,2) H	___
10.8	(2,2) H	(3,2) V	(3,3) H	(2,3) V	___
8.5	(1,4) H	(1,1) V	(4,1) H	(4,4) V	___
7.6	(3,3) V	(2,3) H	(2,2) V	(3,2) H	___
6.7	(1,3) H	(2,1) V	(4,2) H	(3,4) V	___
4.1	(2,3) V	(2,2) H	(3,2) V	(3,3) H	___

NVG-AIDED CONTRAST SENSITIVITY DATA SHEET - 3 CPD

NAME ______________________ **NVG**____________________

CONDITION____

ACTUAL VALUES:

Orientation 1	Orientation 2	Orientation 3	Orientation 4
H V H H	**V V H H**	**V H V H**	**V H H V**
V H V H	**V H H V**	**V V H V**	**H V V H**
V H V V	**H V V H**	**H V H V**	**V H H V**
H V H V	**V H H V**	**H H V H**	**H H V V**

SUBJECT RESPONSE: **CS =** ______

Orientation ___ **Orientation** ___ **Orientation** ___ **Orientation** ___

SCORING:

CONT	Orientation 1	Orientation 2	Orientation 3	Orientation 4	Total Correct
24.8	(3,4) V	(1,3) H	(2,1) V	(4,2) H	___
21.6	(2,1) V	(4,2) H	(3,4) V	(1,3) H	___
18.1	(1,1) H	(4,1) V	(4,4) H	(1,4) V	___
15.3	(3,2) H	(3,3) V	(2,3) H	(2,2) V	___
13.8	(4,1) H	(4,4) V	(1,4) H	(1,1) V	___
12.3	(4,4) V	(1,4) H	(1,1) V	(4,1) H	___
11.6	(1,2) V	(3,1) H	(4,3) V	(2,4) H	___
9.9	(2,4) H	(1,2) V	(3,1) H	(4,3) V	___
9.1	(4,3) H	(2,4) V	(1,2) H	(3,1) V	___
8.0	(3,1) V	(4,3) H	(2,4) V	(1,2) H	___
7.3	(2,2) H	(3,2) V	(3,3) H	(2,3) V	___
6.6	(1,4) H	(1,1) V	(4,1) H	(4,4) V	___
4.7	(3,3) V	(2,3) H	(2,2) V	(3,2) H	___
4.1	(1,3) H	(2,1) V	(4,2) H	(3,4) V	___
3.9	(2,3) V	(2,2) H	(3,2) V	(3,3) H	___
3.0	(4,2) V	(3,4) H	(1,3) V	(2,1) H	___

APPENDIX E

COLLECTED DATA OF ALL TWENTY SUBJECTS

		NVG VA				NVG VA				NVG CS				NVG CS				NVG CS		
	Tri-bar	NVG VA	20/xx			Tri-bar VA 20/xx				12 cpd				6 cpd				3 cpd		
Subject	Baseline VA	baseline	green	red		baseline	green	red		baseline	green	red		baseline	green	red		baseline	green	red
2	15.9	40	50	60		45.1	50.6	56.8		18.3	35.3	100		7.6	11.6	17.9		6.6	6.6	9.9
3	17.9	45	55	60		40.1	56.8	71.6		22.9	31.5	100		8.5	8.5	10.8		6.6	6.6	11.6
4	17.9	40	50	55		45.1	50.6	50.6		18.3	26.1	100		7.6	4.1	8.5		6.6	3.9	3
5	20.1	50	60	55		50.6	56.8	71.6		31.5	22.9	55.2		7.6	8.5	7.6		3	3.9	4.1
6	17.9	50	50	55		50.6	50.6	56.8		31.5	35.3	42.3		7.6	7.6	10.8		3	4.1	7.3
7	17.9	55	60	75		56.8	71.6	80.4		55.2	88.8	100		10.8	10.8	17.9		7.3	6.6	11.6
8	22.6	50	55	60		50.6	56.8	80.4		35.3	63.7	100		7.6	8.5	16.2		6.6	4.7	7.3
9	20.1	45	50	55		50.6	50.6	63.8		28.2	35.3	63.7		6.7	8.5	6.7		6.6	4.1	4.1
10	22.6	60	55	85		56.8	56.8	71.6		42.3	100	100		8.5	10.8	10.8		8	6.6	6.6
11	22.6	50	55	55		50.6	63.8	71.6		35.3	69.1	100		10.8	10.8	10.8		6.6	8	11.6
12	17.9	50	60	60		45.1	50.6	56.8		35.3	42.3	100		8.5	11.6	16.2		6.6	6.6	15.3
13	15.9	50	65	95		50.6	56.8	71.6		49.5	100	100		16.2	28	39		11.6	11.6	15.3
14	17.9	50	55	60		50.6	56.8	63.8		35.3	55.2	100		7.6	16.2	16.2		6.6	6.6	6.6
16	17.9	50	55	70		45.1	50.6	71.6		49.5	80.7	80.7		17.9	21	21		9.9	9.9	11.6
17	20.1	50	55	75		50.6	63.8	71.6		44.4	100	100		7.6	10.8	17.9		6.6	6.6	8
18	20.1	45	55	60		50.6	50.6	56.8		26.1	22.9	55.2		7.6	7.6	8.5		6.6	7.3	8
19	17.9	50	50	60		45.1	50.6	56.8		31.5	49.5	88.8		10.8	10.8	16.2		8	6.6	8
20	20.1	50	50	60		45.1	50.6	56.8		31.5	35.3	63.7		10.8	7.6	12		6.6	6.6	6.6
21	15.9	50	55	75		45.1	56.8	63.8		49.5	100	100		8.5	7.6	16.2		6.6	4.7	8
22	17.9	50	60	75		45.1	56.8	63.8		42.3	100	100		10.8	11.6	17.9		9.9	11.6	12.3
TOTAL	377.1	980	1100	1305		969.9	1109	1308.6		713.7	1194	1750		189.6	222.5	299.1		139.9	133.2	176.8
AVE	18.855	49	55	65.25		48.495	55.45	65.43		35.685	59.7	87.48	7	9.48	11.125	14.955		6.995	6.66	8.84
% CH			0.1091	0.249			0.1254	0.2588			0.402	0.592			0.1479	0.3661			-0.05	0.20871

APPENDIX F

COLLECTED DATA SPLIT-UP BY NVG EXPERIENCED SUBJECTS, PILOT SUBJECTS, AND REMAINING SUBJECTS

NVG EXPERIENCED SUBJECTS

		NVG VA			NVG VA			NVG CS			NVG CS			NVG CS		
	Tri-bar	NVG VA 20/xx			Tri-bar VA 20/xx			12 cpd			6 cpd			3 cpd		
Subject	Baseline VA	baseline	green	red	baseline	green	red	baseline	green	red	baseline	green	red	baseline	green	red
4	17.9	40	50	55	45.1	50.6	50.6	18.3	26.1	100	7.6	4.1	8.5	6.6	3.9	3
18	20.1	45	55	60	50.6	50.6	56.8	26.1	22.9	55.2	7.6	7.6	8.5	6.6	7.3	8
20	20.1	50	50	60	45.1	50.6	56.8	31.5	35.3	63.7	10.8	7.6	12	6.6	6.6	6.6
TOTAL	58.1	135	155	175	140.8	151.8	164.2	75.9	84.3	218.9	26	19.3	29	19.8	17.8	17.6
AVE	19.36666667	45	51.67	58.33	46.933	50.6	54.733	25.3	28.1	72.967	8.6667	6.433	9.67	6.6	5.933	5.867
% CH			0.129	0.229		0.072	0.1425			0.1	0.6533		-0.347	0.1		-0.11	-0.13

SUBJECTS WITH FLYING EXPERIENCE

		NVG VA			NVG VA			NVG CS			NVG CS			NVG CS		
	Tri-bar	NVG VA 20/xx			Tri-bar VA 20/xx			12 cpd			6 cpd			3 cpd		
Subject	Baseline VA	baseline	green	red	baseline	green	red	baseline	green	red	baseline	green	red	baseline	green	red
4	17.9	40	50	55	45.1	50.6	50.6	18.3	26.1	100	7.6	4.1	8.5	6.6	3.9	3
7	17.9	55	60	75	56.8	71.6	80.4	55.2	88.8	100	10.8	10.8	18	7.3	6.6	11.6
9	20.1	45	50	55	50.6	50.6	63.8	28.2	35.3	63.7	6.7	8.5	6.7	6.6	4.1	4.1
18	20.1	45	55	60	50.6	50.6	56.8	26.1	22.9	55.2	7.6	7.6	8.5	6.6	7.3	8
20	20.1	50	50	60	45.1	50.6	56.8	31.5	35.3	63.7	10.8	7.6	12	6.6	6.6	6.6
22	17.9	50	60	75	45.1	56.8	63.8	42.3	100	100	10.8	11.6	18	9.9	11.6	12.3
TOTAL	114	285	325	380	293.3	330.8	372.2	201.6	308.4	482.6	54.3	50.2	71.5	43.6	40.1	45.6
AVE	19	47.5	54.17	63.33	48.883	55.13	62.033	33.6	51.4	80.433	9.05	8.367	11.9	7.26667	6.683	7.6
% CH			0.123	0.25		0.113	0.212		0.346	0.5823		-0.082	0.24			-0.09	0.044

REMAINING SUBJECTS

		NVG VA			NVG VA			NVG CS			NVG CS			NVG CS		
	Tri-bar	NVG VA 20/xx			Tri-bar VA 20/xx			12 cpd			6 cpd			3 cpd		
Subject	Baseline VA	baseline	green	red	baseline	green	red	baseline	green	red	baseline	green	red	baseline	green	red
2	15.9	40	50	60	45.1	50.6	56.8	18.3	35.3	100	7.6	11.6	18	6.6	6.6	9.9
3	17.9	45	55	60	40.1	56.8	71.6	22.9	31.5	100	8.5	8.5	11	6.6	6.6	11.6
5	20.1	50	60	55	50.6	56.8	71.6	31.5	22.9	55.2	7.6	8.5	7.6	3	3.9	4.1
6	17.9	50	50	55	50.6	50.6	56.8	[illegible].5	35.3	42.3	7.6	7.6	11	3	4.1	7.3
8	22.6	50	55	60	50.6	56.8	80.4	35.3	63.7	100	7.6	8.5	16	6.6	4.7	7.3
10	22.6	60	55	85	56.8	56.8	71.6	42.3	100	100	8.5	10.8	11	8	6.6	6.6
11	22.6	50	55	55	50.6	63.8	71.6	35.3	69.1	100	10.8	10.8	11	6.6	8	11.6
12	17.9	50	60	60	45.1	50.6	56.8	35.3	42.3	100	8.5	11.6	16	6.6	6.6	15.3
13	15.9	50	65	95	50.6	56.8	71.6	49.5	100	100	16.2	28	39	11.6	11.6	15.3
14	17.9	50	55	60	50.6	56.8	63.8	35.3	55.2	100	7.6	16.2	16	6.6	6.6	6.6
16	17.9	50	55	70	45.1	50.6	71.6	49.5	80.7	80.7	17.9	21	21	9.9	9.9	11.6
17	20.1	50	55	75	50.6	63.8	71.6	44.4	100	100	7.6	10.8	18	6.6	6.6	8
19	17.9	50	50	60	45.1	50.6	56.8	31.5	49.5	88.8	10.8	10.8	16	8	6.6	8
21	15.9	50	55	75	45.1	56.8	63.8	49.5	100	100	8.5	7.6	16	6.6	4.7	8
TOTAL	263.1	695	775	925	676.6	778.2	936.4	512.1	885.5	1267	135.3	172.3	228	96.3	93.1	131.2
AVE	18.79285714	49.6429	55.36	66.07	48.329	55.59	66.886	36.5786	63.25	90.5	9.6643	12.31	16.3	6.87857	6.65	9.371
% CH			0.103	0.249		0.131	0.2774		0.422	0.5958		0.215	0.41			-0.03	0.266